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19 MAY 1947

RADIOLOGICAL SAFETY

HISTORY OF NAVY MEDICINE

19 MAY 1947

AN INTRODUCTION TO RADIOLOGICAL SAFETY

BUREAU OF MEDICINE AND SURGERY
NAVY DEPARTMENT
WASHINGTON, D. C.

UNITED STATES
ATOMIC ENERGY COMMISSION
WASHINGTON 25, D. C.

May 19, 1947

Joint Crossroads Committee
Main Navy Building
Washington, D.C.

Attention: Commander D. Klein

Subject: Draft copy of "An Introduction to Radiological Safety"

Your request of April 30, 1947, for security clearance of a draft copy of "An Introduction to Radiological Safety" has been received by this office, and the material reviewed for security purposes.

This is to advise that the United States Atomic Energy Commission raises objection on grounds of security to release and publication of the information contained therein. Provided, however, deletions as specified in the attached CONFIDENTIAL memorandum, dated May 19, 1947, Symbol: AECK-81, are made, no objections will be raised by the United States Atomic Energy Commission to release and publication of the information contained in revised manuscript.

Your attention is invited to deletions 2 and 3 as listed in the attached memorandum. While the Declassification Guide does not allow publication of such material, no objection will be raised to publication if this material has been previously published in official JTF-1 or JCC releases. If this material has not been previously published in official JTF-1 or JCC releases, deletion must be made.

Your cooperation in submitting this material for clearance is appreciated.

Corbin Allardice

Corbin Allardice
Office of Information

For: Edward R. Trapnell

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Deletions in paragraph two (2) of basic correspondence have been made as requested.

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INTRODUCTION

It is desirable that all medical officers, in fact all medical personnel, have some general knowledge of the problems relating to the atomic bomb and atomic warfare. In this connection, it is particularly important that they understand some of the strategic and tactical applications, the limitations of defensive measures, and the problems encountered in radiological safety operations. They should have some understanding too, of the devices employed in detecting and measuring radiological hazards, the principles of avoidance, and also the relationship of medical personnel to commanding officers in the capacity of technical advisor. It is emphasized that radiological safety implies all of the phases of atomic explosion from the initial production of fissionable material until long after the actual bomb burst. The medical officer must include within his province not only his normal medical duties but also his duties as a staff officer, a technical advisor, and a supervisor in matters of preventive medicine and decontamination.

An attempt is made, therefore, to include herein a brief, and it is hoped interesting, summary of fundamental information which will give all medical personnel a concept of the problems involved and a basis for further training in this most important field of medicine. The possibilities of atomic medicine are as unlimited as those of atomic warfare and it is hoped that enough interest will be evinced by those who read this to necessitate the preparation of more advanced courses of personalized instruction for those who request them.

NUCLEONICS

I: The Structure of Matter

MOLECULES AND ATOMS

The Non-Continuity Of Matter

IT WILL BE advantageous to examine our ideas of the world about us, forgetting for the moment that we have ever heard of atoms and molecules. Let us naively base our ideas on only those conclusions which we can draw from our five senses. For example, consider the structure of a simple block of lead. If we have a six-inch cube, we know that we could cut the lead into smaller cubes with little difficulty. We might be able to make a quantity of smaller cubes one-tenth or even one hundredth of an inch in thickness. Is this the limit of division? No—with intricate machinery, such as that used in manufacturing the gratings of spectroscopes, we could make even smaller divisions of the lead, down to a ten-thousandth of an inch.

Is there, then, any limit to the subdivision of the material which we could accomplish, provided that we could obtain suitable machinery? Yes, it has been found that this subdivision could not be continued beyond a figure of approximately 10^{-8} cm. ($10^{-8} = \frac{1}{10^8} = 0.000,000,01$) and still have the material retain its identiy and characteristic properties. *The smallest particle which retains the properties of the substance in question is known as the MOLECULE.*

We need not confine our thoughts to solid materials. Imagine the division of a drop of water into smaller and smaller droplets until the ultimate molecule of water is reached. Since the molecular size is extremely small, there will be a great many of these molecules in even a small quantity of material. Thus the number of molecules in a teaspoon of water is about 10^{23} (1 followed by twenty-three cyphers). This huge figure is more than the number or drops of water in Lake Michigan. It is also the approximate number of molecules in the same volume for all common liquids and solids, the densities of which do not vary greatly, and the molecular structures of which are not too complicated.

However, we know that gases are much less dense than liquids and solids, so that a given volume of any material in the gaseous state will contain fewer molecules than an equal volume of the material in the liquid or solid state. For example, if we heat the spoonful of water until it vaporizes into steam at atmospheric pressure, it will then occupy a volume of approximately five liters or about 300 cubic inches. The increase in volume has been over a thousand fold, and since the number of molecules present has not changed, we must conclude that most of the gas or steam consists of empty space. This must be true unless the molecules themselves have expanded, an assumption which has been proved false.

Thus it can be seen that the gas or vapor does not consist of continuous matter, but of great empty spaces, with molecules of matter scattered in these spaces. Even with the denser solids and liquids, it can be shown that a large proportion of the volume they occupy is also empty space. This will be explained shortly.

The Kinetic Theory

There are many common characteristics of gases which can be explained from the molecular assumption.

We know that if we take a certain volume of a gas, as in a cylinder fitted with a piston, the gas volume will decrease if pressure is applied to the piston, and increase when the pressure is released. Also, if the gas is heated without changing the pressure on it, we know that it will expand. When it cools, the volume will decrease. To retain the same volume during the cooling process, the pressure on the piston must be reduced.

Observations such as these have led to the development of the *kinetic theory of gases.* In brief, it is assumed that the molecules of a gas act like tiny, hard spheres of matter, and that they are in constant motion inside their container, flying about at great speeds in all directions. The space between the molecules is large, so that they can go some distance before colliding with one another or with the walls of the container. When they do collide, the collisions are elastic, meaning that no energy is lost; the kinetic energy is merely transferred from one molecule to another. If the gas is cooled, the molecules move more slowly —if it is heated, they speed up.

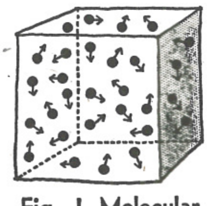

Fig. 1 Molecular Motion According to Kinetic Theory.

These assumptions explain many of our observations on gases. The pressure of the gas is caused by the impact of the many collisions of the molecules against the container walls. Thus, if the size of the container (and the gas volume) is decreased the molecules become more crowded; there are more of them striking the wall in a given time; consequently the impact (pressure) rises. A very simple relation exists here, expressed as $P_1V_1 = P_2V_2$, where P is pressure, V is volume, and the subscripts refer to the conditions initially and finally. Of course, the amount or mass of the gas must remain constant, and the units of P and V must be consistent. Furthermore, the temperature must not change during the experiment.

The *temperature effects* on the gas can also be explained by the kinetic theory. When the gas is heated, the molecules move more rapidly, and thus exert a greater impact on the container walls. This increased impact raises the gas pressure. However, if it is desired to retain a constant pressure, the volume of the gas must increase, so that there will be fewer of these more vigorous collisions per second on a given area of the container than there were before the gas was heated. At constant volume, the relation is $P_1/T_1 = P_2/T_2$, and at constant pressure $V_1/T_1 = V_2/T_2$. Here T is the gas temperature expressed in degrees above absolute zero. Absolute zero is the temperature at which the molecular motion ceases entirely, and is the lowest temperature theoretically obtainable. It has the value of 273° below zero on the Centigrade scale, and 460° below zero on the Fahrenheit.

One more useful concept about gases is embodied in "Avogadro's Law," which states that equal volumes of gases at the same pressure and temperature contain equal numbers of molecules. This law was based on evidence observed in the combination of various gases, and has led to many useful conclusions. The reader is requested to remember what was just said about the motion of gas molecules, and collisions between various molecules.

The distance which a molecule moves on the average before colliding with another molecule, is known as the *mean free path.* This will be discussed in more detail in a later section. The mean free path depends on the temperature, the pressure, and the nature of the gas itself. Under ordinary conditions of temperature and pressure it has a value of about 10^{-5} cm. for all common gases.

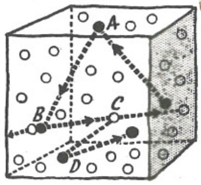

Fig. 2 Molecular Mean Free Path. The dark molecule's path is traced as it collides with the container walls at points A and D, and with other molecules at B and C. The average distance between successive collisions at B and C is defined as the molecular mean free path.

It must not be concluded that all molecules are simple structures—many are very complex. Most molecules are not spheres, as we

have assumed above for purposes of simplification. Actually they vary greatly in size and structure, from the very simple helium molecule to the complex ones of glass, proteins, or synthetic rubber. The molecule weights of these complex molecules may be as high as a million. The *molecular weight* of a substance is defined as the weight in grams of a fixed number of its molecules. This fixed number is called Avogadro's number and is about 6.0×10^{23}. It is not so important to know this number, as to remember an important conclusion based on the definition of the molecular weight. Since a molecular weight of any particular substance contains the same number of molecules (Avogadro's number) as a molecular weight of any other substance, the ratio of the weights or masses of individual molecules is the same as the ratio of their molecular weights.

To demonstrate the magnitude of molecular sizes, suppose we try this simple method of measuring molecular diameter: Let us take a known quantity of an oil and allow it to spread into a film on the surface of a tank of water. If we confine the film by a wire frame with one movable edge, then pull out this movable edge to a certain point, we find that the film reaches a maximum size, and then breaks, becoming spotty or discontinuous. It is reasonable to assume that the film has stretched until it is only one molecule thick, and has then broken when it could stretch no farther. Now measure the area of the frame. From the weight of the oil (measured before the oil was placed on the water) and from its molecular weight determined by an independent experiment, the number of molecules in the film may be calculated. We can

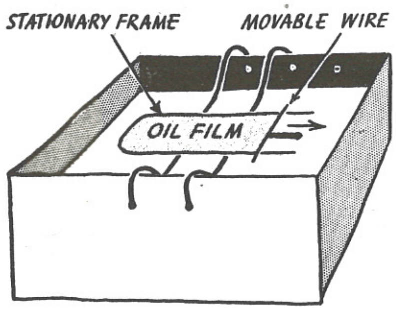

Fig. 3 Determination of Molecular Diameter.

then calculate the area occupied by each molecule, and from this the molecular diameter. Answer — molecular diameter $= 10^{-8}$ cm. approximately.

We have seen that the molecule is the smallest division of matter which allows a particular substance to retain its identity and characteristic properties. Since there are so many different materials on earth, there must be many different kinds of molecules. Thus we have molecules of water, sugar, salt, glass, hydrogen, etc. Several hundred thousand different substances occur naturally and are known to the chemist. Not content with this quantity, the chemist synthesizes rayon, nylon, synthetic

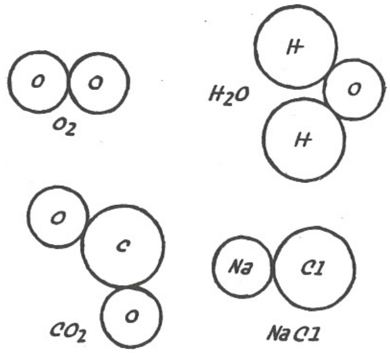

Fig. 4 Molecules of Simple Materials.

rubber, sulfa drugs and dyes, making tailor-made molecules of the desired properties, to suit his particular needs. Today, he has made over a half million different molecules not found in nature, and there is no reason to think that he cannot make many more. Hence, if there were no simpler method of classifying the various substances than by the molecules which compose them, chemistry would be even more complicated that it is, and would be as much a puzzle to the average chemist as to the average layman. Fortunately, the situation is not so bad. Further classification of substances is possible.

The Atom

It has been found that these multitudinous chemical materials are composed of only ninety-two stable *elements* and several hundred of their isotopes (which will be explained later), plus a few more recently discovered unstable elements. We define these elements as materials which can not be further subdivided into simpler substances by any chemical means.

The smallest division of an element, we call the *atom*. Thus we have the elements oxygen, carbon, hydrogen, iron, lead, etc., and can talk about atoms of these materials. But sugar is not an element since it is composed of atoms of carbon, hydrogen and oxygen, which are combined into sugar molecules. Since the sugar molecule can be broken down by chemical means into smaller and simpler units, we cannot have sugar atoms. Likewise, salt is a combination of atoms of chlorine (Cl) and sodium (Na), two more elements.

Chemical Reactions

The atoms combine with one another to form molecules under proper conditions, and there is always an energy effect which accompanies their combination. (There are a few examples of materials, the molecules of which are composed of single atoms, e.g., helium, argon.) Thus a pound of hydrogen combines, or burns, with eight pounds of oxygen to form nine pounds of water, and in so doing liberates energy in the form of approximately 60,000 btu of heat. A btu (British thermal unit) is the amount of heat necessary to raise the temperature of one pound of water by one degree F. This combination of the hydrogen and oxygen gives enough heat to raise the temperature of 340 pounds of water from its freezing point to its boiling point, or to convert 44 pounds of ice to steam. Such a reaction is called "exothermic," which means that it liberates heat.

If we wish to recover the original hydrogen and oxygen from our nine pounds of water, we would have to add to it 60,000 btu of heat, or its equivalent in other energy forms, to break the water molecules apart. We might do this by heating the water to a sufficiently high temperature, or by running an electric current through it. The latter would be a more practical method. We conclude that since 60,000 btu (or its electrical equivalent of 16 kw. hrs.) is needed to break this quantity of water molecules into their component atoms, these atoms must be held together with a considerable force.

There are also many examples of "endothermic" reactions, in which heat must be added to cause the reaction to proceed. Thus, if we took a pound of hydrogen and combined it with twelve pounds of carbon under conditions which would result in the formation of acetylene, we would find it necessary to add 52,000 btu to make the reaction go. Consequently, we should not expect the acetylene molecule to be very stable. As a matter of fact, it is very unstable, the molecules tending to break down into elemental carbon and hydrogen atoms; the liberation of considerable energy accompanies this reaction. This is the reason why so many precautions must be observed in the packing of acetylene cylinders for bottled gas uses. Special materials must be added to the acetylene to prevent its spontaneous decomposition with disastrous results.

The chemist often says that compounds such as acetylene are in a "metastable" state, meaning that they can spontaneously break down, with the liberation of energy. Water is stable, chemically speaking. There is no chance that water at room temperature will break down into hydrogen and oxygen, unless a large amount of energy is put into it.

It will be useful to point out an analogy from hydraulics to illustrate chemical reactions. Let us consider spilling a bucket of water on a level floor. There is no tendency for the water to move from its position, and it can do no work. Nor has it any potential energy. It is in a stable condition. Now suppose we spill a bucket on a hill side. We know that the water will flow down hill, and can do work in "seeking its level," the amount of work depending on the height from which the water flows. This water is in an unstable position. A third example is a bucket of water in a crater on top of the hill.

We know that it is possible to get work from the water if it flows down hill, but first we must lift it over the

lip of the crater so that it can flow down hill. Thus, it is in a metastable condition. The amount of energy which we obtain from the water in flowing down the hill is similar to the heat of reaction which was obtained in the combination of the hydrogen and oxygen, or the decomposition of the acetylene. Similarly, the amount of work we must do to raise the water over the lip of the crater is analagous to what the chemist calls "activation energy," and is the amount of outside energy which must be added before the reaction will begin.

We ask the reader to study carefully the concepts of *reaction* and *activation energy*, and of *stable*, *unstable* and *metastable states*, as these

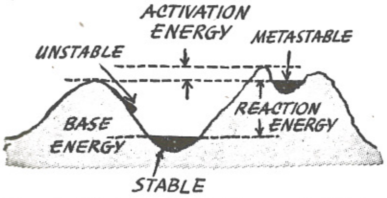

Fig. 5 Stable, Unstable and Metastable States.

terms will be used during the course of the subsequent discussions.

To recapitulate, we see that molecules are formed from atoms in various combinations, and that the stability of the molecules depends on the energy relations of their formation. The chemist writes "equations", which are merely shorthand notations of the reactions involved. For example, if hydrogen combines with oxygen to form water, we write—

$$2H + O = H_2O.$$

In longhand this means that two atoms of hydrogen combine with one atom of oxygen to form one molecule of water. Or two million atoms of hydrogen combine with one million of oxygen to form one million molecules of water. Or again 6.0×10^{23} atoms of oxygen combine with 12.0×10^{23} of hydrogen to form 6.0×10^{23} molecules of water. We recall that the figure of 6.0×10^{23} was the number of molecules of any substance which has by definition a weight equal to the *gram molecular weight* of that substance. The word "mole" or "gram mole" is just an abbreviation for either gram molecular weight or gram atomic weight. Thus, we say that two moles of hydrogen atoms plus one mole of oxygen atoms form one mole of water.

We have said that molecules are formed by the combination of various atoms. Most molecules are formed from atoms of different elements, but some molecules are formed from two or more atoms of the same element. Thus, two atoms of hydrogen form a molecule of hydrogen, and two atoms of oxygen form a molecule of oxygen. However, a molecule of helium contains only one atom, while under certain conditions a molecule of sulphur consists of eight sulphur atoms. Since elements are usually in molecular form during chemical reactions, the chemist prefers to write his equations in molecular rather than atomic form, thus:

$$2\ H_2 + O_2 = 2\ H_2O$$
$$4\ \text{gm} + 32\ \text{gm} = 36\ \text{gm}$$

The weight of a mole (6.0×10^{23}) of hydrogen atoms is one gram; there are two atoms to a molecule; and we used two moles of hydrogen. Therefore, the weight of hydrogen is $1 \times 2 \times 2 = 4$ gms. Likewise, the weight of a mole of oxygen atoms is 16 grams, there are two atoms to the molecule, and we used one mole; hence; there are $16 \times 2 \times 1 = 32$ gm of oxygen. Each molecule of water consists of one atom of oxygen and two of hydrogen, and there will be 16 plus $2 \times 1 = 18$ gms per mole of water. Since we have two moles of water, the weight of the water is $2 \times 18 = 36$ gms.

Notice that the number of atoms of each element is the same on the left side of the equation as it is on the right, and the total weights are also the same. This is why we speak of the shorthand statement as a "chemical equation". This is not surprising since we have previously said that atoms cannot be destroyed by chemical means, and common sense tells us that we should not lose or gain any mass of weight in the reaction. When we consider nuclear reactions, a little later on, we will see that these statements are not altogether true.

II: Structure of the Atom

PROTONS, ELECTRONS AND NEUTRONS

The Electrical Nature Of Matter

IN THE FIRST SECTION we saw how all matter is composed of fundamental building blocks called molecules, which are the smallest structural units retaining the identity of a substance. We also saw that the molecules in a gas are far apart, and are moving back and forth in empty space like little, hard spheres. It was then stated that molecules are composed of atoms, in various arrangements, and that all of the many thousands of chemical compounds can be formed from only ninety-two stable elements. The stability of compounds depends upon the energy relations of their formation from their component atoms.

We also found that the diameter of the molecule is about 10^{-8} cm. This is only an approximate size, as we should expect the heavier and more complex molecules, composed of many atoms, to be larger than the lighter, simpler ones. However, if one recalls from his geometry that the volume of a sphere is proportional to the cube of its radius, he will see that there can be considerable variation in molecular volume and weight, without the molecular diameter changing very much. This is assuming the molecules to be spherical.

What about the size of the atom? It is believed that the atoms in a molecule are very close together, even overlapping one another (we shall see shortly how this is possible), so that atomic diameters are of the same order of magnitude as molecular diameters. For simplicity we shall assume that the atomic diameter is also about 10^{-8} cm.

The question now arises concerning the structure of the atom. Is the atom merely a little hard sphere? If so, what is the reason for atoms to unite into molecules? What is the nature of the forces binding the atoms?

Let us see what we can do about answering some of these questions.

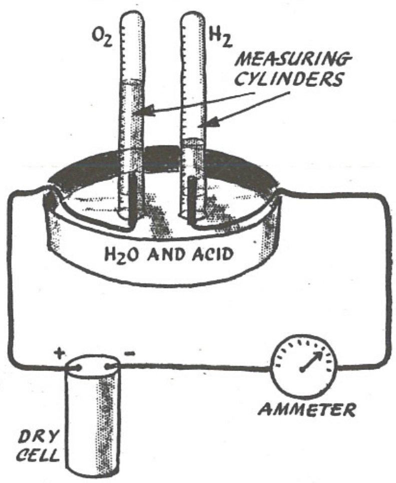

Fig. 6 Faraday's Experiment—Electrolysis of Water.

Although most of the knowledge concerning the structure of the atom has been revealed during the past fifty years, even as far back as the middle of the 19th century the problem was undergoing extensive investigation. The famous English scientist, Michael Faraday, discovered some very interesting information by running d.c. electrical current through water mixed with a little acid. (See figure 6) For example, he found that the current broke water into its fundamental elements, and that hydrogen collected at the negative electrode (cathode) while oxygen collected at the positive electrode (anode). The volume of the hydrogen was *exactly twice* that of the oxygen. This is just what we would expect, since one molecule of oxygen always combines with two molecules of hydrogen, and by Avagadro's Law, we know that equal volumes of gases under the same conditions of pressure and temperature contain equal numbers of molecules.

Faraday also found that for the same amount of electricity run through the solution, the same number of molecules of hydrogen would

always be formed. The formation of one mole of hydrogen atoms, or a half mole of hydrogen molecules, requires a unit of electricity known as the *faraday*, which is 96,500 coulombs. A *coulomb* is simply the number of negative electric charges carried by a current of one ampere in one second. By studying the "electrolysis" of many materials, Faraday found that in order to deposit a mole of an element, one, two, three, up to eight faradays were required, depending on the element in question. Thus, one faraday was required to deposit a mole of hydrogen, sodium, chlorine, or silver, while copper, magnesium, and oxygen required two, and aluminum three. How can we explain Faraday's results?

By passing a current through some molten sodium chloride (NaCl), which is the chemical name for common table salt, we can conduct an experiment which is a little easier to understand than Faraday's, but still based on the same principle. In this experiment, the salt is broken down into its elements, chlorine collecting at the anode, and sodium at the cathode. (See figure 7.)

Since like charges repel and unlike charges attract, we conclude that sodium atoms carry a positive charge and chlorine a negative charge, and that the charges on these atoms are neutralized by opposite charges at the electrodes.

The chemist says that sodium and chlorine atoms in the molten state are really not normal atoms, but have charges—the sodium a positive charge and the chlorine a negative charge. Such charged atoms are called *ions*, and the process of producing them is known as *ionization*. Since unlike charged bodies attract, the sodium and chlorine ions are attracted toward each other and combine to form sodium chloride molecules. This attraction is sufficiently strong to form the stable molecule in the solid state. However, if the salt is melted, the molecules are broken down into ions, and these ions conduct an electric current. The ions are then neutralized at the electrodes and the un-ionized atoms collect as the free elements.

By extending this explanation to other materials, we can deduce that oxygen and copper ions must carry *twice* as much charge as chlorine and sodium ions, since *two* faradays are required to produce a mole of copper or oxygen. Similarly, since aluminum requires *three* faradays per mole, it must be *triply* charged.

Such observations as those we have described, coupled with others in the fields of radioactivity, spectroscopy, etc., which we do not have time to discuss, led scientists to conclude that the forces holding atoms together are largely electrical in nature. The atoms themselves consist of bundles of electrically charged particles, both positive and negative. The positive and negative quantities of electricity are equal, so that the atom as a whole is electrically neutral. However, this does not mean that the various parts of the atom are neutral. Ionization is explained as the process of losing or gaining electrical charges by the atom. Thus, if an atom loses a negative charge, it becomes a positive ion, while if it loses a positive charge (or gains a negative charge, which would have the same effect), it becomes a negative ion.

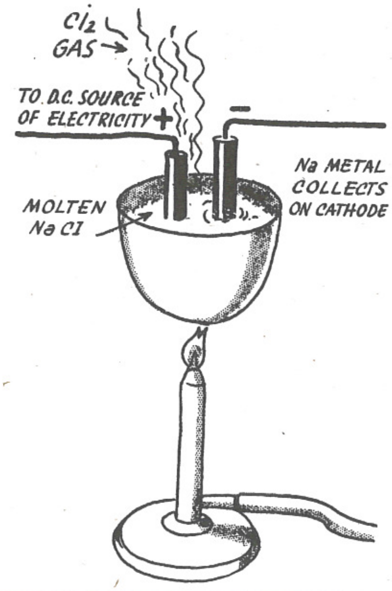

Fig. 7 Electrolysis of Salt.

Bohr's Model of the Atom

As we just saw, the atom is really an aggregation of charged particles of matter, half charged positively and half charged negatively. Early workers, such as J. J. Thomson, thought that the atom was like a bean bag filled with equal numbers of "positive" and "negative" beans, homogeneously distributed in the bag. (See figure 8.) But experiments carried on by Lord Rutherford and others showed that this could not be a true representation of the atomic model. Let us consider what would happen if we started to shoot at one of the bean bags with a high speed B-B gun, or a low speed 22 rifle. We would expect the bullets to be slowed down in going through the bag, and slightly deflected from their course by collisions with the beans in the bag. In fact, if we knew the size and density of the beanbag and the mass velocity of the bullet, it would not be too difficult to calculate just how much the bullets would be deflected and slowed. Rutherford carried on such experiments, except that he shot at atoms instead of bean bags, and for bullets he used high speed particles, called "alpha particles". There will be discussion of the origin and nature of these alpha particles in Section IV.

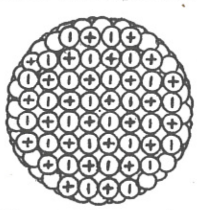

Fig. 8 Thomson's Model of the Atom.

Rutherford had enough information to calculate how much his alpha particles should be deflected, but the results did not agree at all with his calculations. He found that most of his bullets were deflected only a very small amount, while a very few were deflected greatly, some even being reflected backwards by the atom. His calculations indicated that all of them should be deflected at some intermediate value. The only way that Rutherford could explain his results was by assuming that instead of being composed of a homogeneous mass of material, the atom was really composed of a very dense, small center, or nucleus, plus a shell of lighter particles at a considerable distance from the nucleus. Rutherford reasoned that *most of the volume of the atom is merely empty space.*

Several years later Niels Bohr, a Danish physicist, assembled all of the available data of physics and chemistry on atomic structure, and presented his theory of the atom. This theory has explained a great many of the phenomena observed, and is of such value that Bohr was awarded the 1912 Nobel prize. Prof. Bohr has also contributed important work to the atomic bomb project. According to him the atom really looks a great deal like our solar system. At the center is a massive, dense nucleus, corresponding to our sun. At a great distance away from the center are many lighter particles, which spin around it in circular or elliptical orbits, just as the earth and other planets revolve around the sun. Just as most of the volume of the solar system is empty space, similarly, the atom, a miniature solar system, also is mostly empty space. Bohr said that the central mass was composed of a varying number of closely packed, positively charged, heavy particles, called *protons*. The particles flying around the nucleus are much lighter, and are negatively charged. These are called *electrons.*

According to Bohr, the properties of elements are completely determined by the number of protons and electrons contained in the atoms of the elements. We present diagrams of a few of the simpler atoms, asking the reader to pay particular attention to the small volume occupied by the nucleus, and the large amount of free space. (See figure 9.) We also emphasize the small mass of the electron as compared to that of the proton. The proton is about 1840 times heavier than the electron, so that the mass of the atom is mostly determined by the number of protons. Thus, an atom of hydrogen, which has only one proton, is said to have a mass of one. The next atom, that of helium (He) has a mass of four (relative to hydrogen), although it has only two protons. The rest of its mass comes from the presence of two additional fundamental particles, called *neutrons.*

A neutron is merely a proton without its charge, or a proton combined with an electron. Thus the neutron

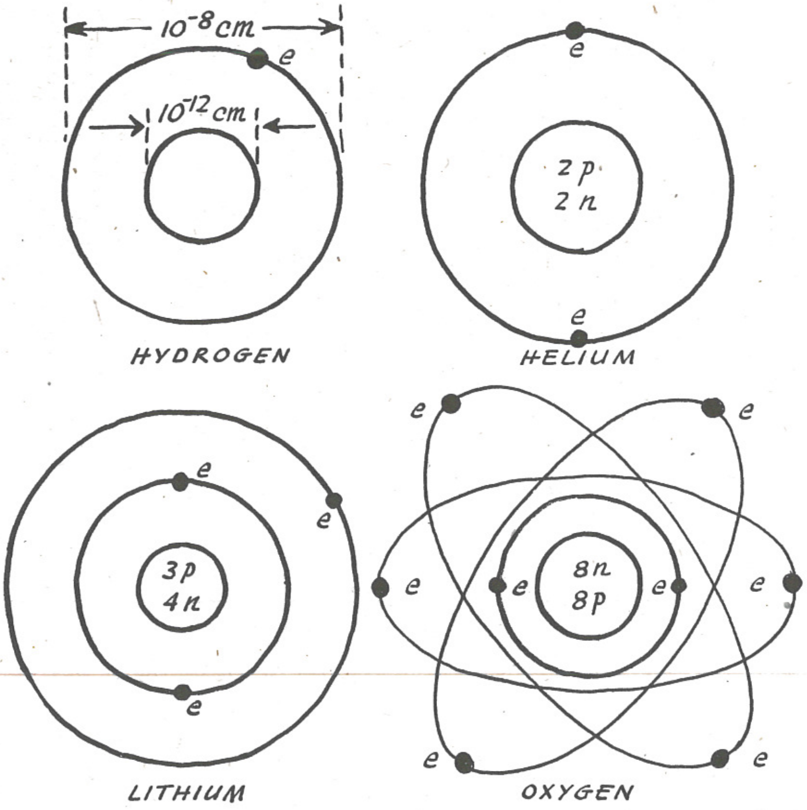

Fig. 9 Rutherford-Bohr Atomic Models.

has no charge, but its mass is nearly the same as that of the proton, since the electron contributes only a very small amount of mass. Sometimes, we speak of protons and neutrons under the common name of *nucleons*, since they are both found in the nucleus. Except for the difference in charge, and properties related to charge, there is no great difference in the properties of the two particles. *Theoretically at least*, we see that a proton can become a neutron if its charge is neutralized by that of a negative electron. Conversely, the neutron can be converted to a proton by combining with a particle known as a *positron*. This is a particle which has the same charge and mass as an electron, but its charge is positive rather than negative. Positrons are not very common, and we will not be concerned with them for the present. We must emphasize that the combinations of the various particles as just given, are presented only as an aid in forming a picture of the relationships between them. This presentation does not give a strict explanation of the actual processes occurring, as these processes are much more complicated.

Reconsidering, we now say that the mass of an atom is determined by the sum total of its protons and neutrons. However, the chemical properties of the element or atom are determined by the electrons which it contains. The electrons are in various orbits around the nucleus, and we can easily see that the total number of external electrons must be the same as the number of protons in the nucleus, since the atom as a whole is electrically neutral. The atoms of each element possess a definite number of orbits in which the electrons revolve, and these orbits are at fixed distances from the nucleus. Some of the orbits are called stable or "unexcited," since the atoms are in their most stable states when the electrons are revolving in these orbits. The other orbits are "excited" and correspond to less stable states. Energy is emitted when an electron moves from an excited to a stable orbit. The energy is manifested by electromagnetic radiations, such as ultra-violet, visible, or infra red light, and gives rise to spectral lines. Each element has its own characteristic spectral lines, and studies of them give much information on atomic structure.

For hydrogen there is only one unexcited orbit; for lithium there are two, and so on. The orbital arrangement becomes very complex for heavy elements, which contain many protons in their nuclei and therefore many electrons outside the nucleus.

Of particular interest to the chemist are the electrons in the outermost orbit, the so-called "orbital electrons." These determine the *valence* of the element. The valence of an element is merely the number of hydrogen atoms one of its atoms will combine with, or if the element does not combine with hydrogen, it is the number of hydrogen atoms one of its atoms is equivalent to, or will replace. Thus, since the formula for water is H_2O, one oxygen atom combining with two hydrogen atoms, the valence of oxygen is two. If we combine copper (Cu) with oxygen, we get a compound CuO or copper oxide. Here the copper has replaced the two hydrogen atoms, and its valence is also two. Similarly for aluminum the valence is three, and so on.

Another way to determine the valence of an element is by electrolysis of one of its compounds. The number of faradays required to obtain a mole of the element in question is also its valence. This method permits distinction between the elements with positive valences and those which have negative valences. If the element *combines* with hydrogen, or is deposited at the *anode* on electrolysis, its valence is *negative*. If it *replaces* hydrogen, or is collected at the *cathode* on electrolysis, its valence is *positive*.

The number of protons in the nucleus (or of electrons outside the nucleus) is very important in determining chemical properties, and is spoken of quite frequently as the *atomic number*, Z. The *atomic weight*, A, is also important, especially in determining the physical properties of an element. The atomic weight is equal to the total number of protons and neutrons, as stated previously. We will make frequent use of these two numbers. The values of A and Z for the various elements may be found in the Periodic Table, which is a systematic arrangement of the elements according to their atomic numbers. (See page 51.) This is a handy reference chart.

III: Nuclear Structure

FISSION AND FUSION

Isotopes

WE HAVE SAID that an element is completely defined in structure and in properties by its atomic number and atomic weight. Of the two, the atomic number is the more important, since it determines the chemical properties, energies of reaction, etc. It is possible for two atoms to have the same atomic number, but different atomic weights. Such atoms, differing only in the number of neutrons in their nuclei, are known as *isotopes*.

Practically, every element as found in nature is really a mixture of two or more isotopes. Thus, ordinary hydrogen consists of three isotopic forms, all of which have an atomic number of one, but possess atomic weights of 1, 2, and 3. The isotope of atomic weight 1 is by far the most abundant, composing about 99.98% of the total hydrogen. The isotope of atomic

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weight 2 is known as *deuterium* or "heavy hydrogen," and occurs to the extent of only 0.02% of the total hydrogen. The third isotope, called tritium, is even less abundant than deuterium, and not of much interest to us. (See figure 10.)

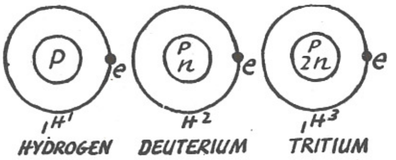

Fig. 10 Isotopes of Hydrogen.

Since deuterium has an atomic number of one, and an atomic weight of two, it must consist of a nucleus containing one proton and one neutron, and have one electron revolving around the nucleus. If we remove the electron from the deuterium atom, we have produced an ion, called a *deuteron.* Obviously this ion has twice the mass of a proton, but the same charge as the proton. Deuterons are important "bullets" for use in bombarding the atom in experiments similar to that of Rutherford, described on page 16.

We find that the isotopic forms of hydrogen exist not only in the free state, but also in compounds. The same is true of the isotopes of the other elements. As an example, when hydrogen combines with oxygen to form water, it forms not only H_2O of molecular weight 18 (16 plus 2 x 1), but also a small quantity of D_2O of molecular weight 20 (16 plus 2 x 2). The latter is known as "heavy water," and is important in nuclear physics work. The proportion of heavy water in ordinary water is, of course, only 0.02%, but there are means of separating the two.

With most substances, the ratio of one isotope to all the others is so high that the atomic weight of the mixture is practically that of the most abundant one, and the atomic weights, in ratio to that of hydrogen, are whole numbers. This would be expected, since most of the weight of the atom is in its nucleus, which is composed of an integral number of protons and neutrons of very nearly the same weight. In fact, the observation that most atomic weights are integral multiples of that of hydrogen was one of the first pieces of evidence for the existence of the nuclear particles, and a strong basis for the atomic theory.

However, the isotopes may be present in nearly equal proportions, in which case the atomic weight will not be near a whole number. This is true for chlorine, which has an atomic weight of 35.5. For a long time chemists were at a loss to explain this discrepancy. Later it was clarified by the discovery that ordinary chlorine is a mixture of isotopes of atomic weight 35 and 37, in the ratio three to one. The value of 35.5 is merely the weighted mean of these two numbers.

The device by which isotopes were discovered and measured is known as the mass spectrograph (see figure 11). The principle of its operation is that ionic isotopes of different masses will be deflected by different amounts when placed in a magnetic field. The atoms to be studied are ionized by means of an electrical discharge and confined in a narrow beam by being made to pass through a series of narrow slits. They are then led into a strong magnetic field, which deflects them from their straight line path into paths which are circular arcs.

Those readers who are familiar with the "right hand rule for motors" in electricity will recall that a wire carrying a current in a magnetic field perpendicular to it, will be deflected in a direction at right angles to both the wire and the field direction. The force causing the deflection is proportional to the current strength. Since a stream of ions is really an electric current, the same situation will hold for such an ionic stream. Here the deflecting force is proportional to the ionic velocity. Accelerating the ions in an electric field before they enter the magnetic field gives a uniform energy to all of them. The velocity of the heavy ions is then less than that of the light ones; consequently the heavy ones are less affected by the magnetic field. The heavy ions move in a circle of large radius and can be collected through a slit, or caught on a photographic plate. The light ions, being more affected by the magnetic field, move in a circle of smaller radius (greater curvature), and can be collected in a slit a distance away from that of the heavy ions, or caught on a plate at another position. From the positions at which the ionic beams struck the photographic plate, Aston, the inventor of the mass spectrograph, was able to measure isotopic masses with great accuracy. We shall see in the next section the importance of obtaining very precise isotopic masses.

Inside the Nucleus

The observant reader will notice that there has been a purpose in our presentation during the first three sections. Beginning with an extremely large number of substances, in various forms and combinations, we have shown that all of these substances are made up of a half million or so different molecules. A simplification resulted when we found that all of the molecules could be constructed from only 92 or so different atoms or chemical elements. Then we learned that these atoms are really built from only a few very fundamental particles — neutrons, protons, electrons, and positrons.

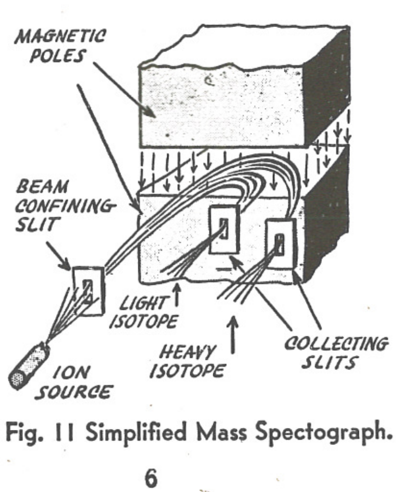

Fig. 11 Simplified Mass Spectograph.

An even further "simplification" is possible, says the modern physicist who understands quantum mechanics. Quantum mechanics finds it necessary to accept hypotheses not compatible with the concepts of classical physics. According to quantum mechanics, there are really no such things as the different particles; they all are merely waves or pulses of energy which can be represented by mathematical equations. To the "quantum mechanic," it is immaterial whether or not we can draw a picture or conceive of a model consistent with our common conceptions of space and material. Thus the average reader or student, unless he has extensive training in advanced physics, finds it difficult to visualize what the quantum mechanic is talking about. In this discussion, therefore, we are limited to retaining our antiquated ideas of electrons and protons, etc., in the interest of simplicity of presentation.

We previously stated that the nucleus of the atom is made up of a varying number of protons and neutrons. It is convenient to think of these nucleons as little droplets of a liquid, and the nucleus itself, as a larger drop composed of the smaller ones fused together. Of course, the properties of this nuclear liquid will be considerably different from those of an ordinary liquid; for instance, its density will be much higher. If we compare its density to that of an ordinary atom, we find that it is much higher than that of the atom as a whole. This follows since the atom is composed of mostly empty space, and practically all of its mass is concentrated in the nucleus, the volume of which is very much smaller than that of the atom. The reader can easily calculate for himself the value of the nuclear density, knowing the weight of an atom or nucleus, and its volume, that of a sphere of diameter roughly 10^{-12} cm. The weight of an atom is the gram atomic weight of the element considered, divided by Avogadro's number.

By this method, the nuclear density is shown to be tremendous—10^{14} grams per cubic centimeter, compared to one gram per cc. for water. This means that *a drop of nuclear fluid big enough to be seen would weigh ten million tons!* Lest the reader doubt the existence of such heavy materials, it is interesting to point out that the white dwarf star known as the companion of Sirius has a density about one hundred thousand times that of water, and higher densities than this are believed to have occurred in the sun and stars before the formation of the present universe.

One very characteristic and important property of liquids is their "sur-

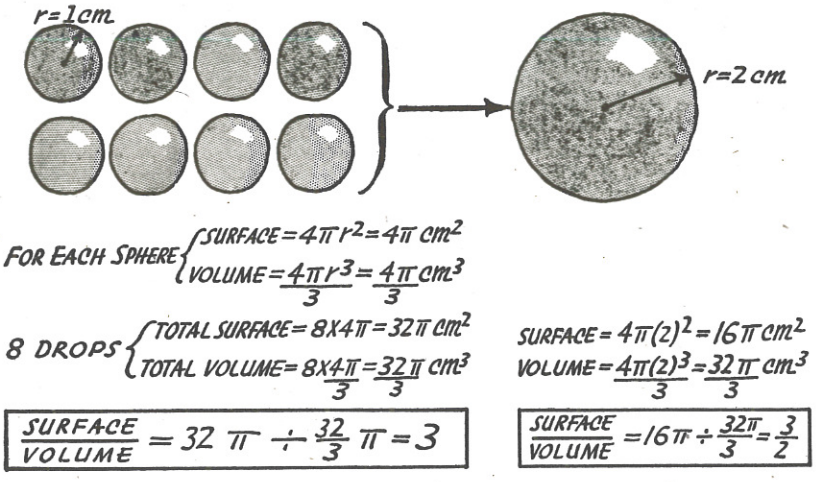

Fig. 12 Fusion of Small droplets causes decrease of Total Surface Area.

face tension." Surface tension is a force which tends to make large droplets out of small ones. Large droplets have a smaller surface area for a given amount of volume or mass than do small ones (see figure 12). The surface of a liquid represents potential energy, and all systems tend to change into the most stable states. Thus, the large droplets (less energy) are more stable than small droplets (more energy). The reader may check this for himself by remembering that the surface of a sphere is $4\pi r^2$ while the volume is $\frac{4\pi r^3}{3}$. Thus a drop of radius one cm has a surface of $4\pi cm^2$, and a volume of $\frac{4\pi}{3}cc$, and its surface to volume ratio is 3. But a drop of radius two cm has a surface of $4\pi \times 2^2$ or $16\pi\, cm^2$ and a volume of $\frac{4}{3}\pi \times 2^3$ or $\frac{32\pi}{3}cc$. Its ratio of surface to volume is only 3/2. To put it another way, we can use these figures to show that the volume of eight drops of radius one cm. is the same as that of one drop of radius two cm., but the surface area of the eight drops is twice as great as that of one drop. If we combine the eight small drops into one large one, there will be a reduction in the total surface area, and therefore in the potential energy equivalent of the surface area of the system. Thus when small drops coalesce to larger ones, energy is liberated. This is the reason that small droplets of mercury on a desk rapidly combine with one another, when they are brought into contact. The value of this surface tension energy is about 75 ergs per square cm. of surface (for water). Converting to English units, the amount of surface energy is about 10^{-2} ft. lbs. per square foot of surface. This is a rather small amount of energy. However, the situation is greatly different with the nuclear fluid. Here the surface tension is 10^{19} ergs per sq. cm., so that the energy of a square foot of nuclear surface is about 10^{15}, or a million billion ft. lbs. per sq. ft., which is quite a lot of energy.

Evidently the surface tension forces in the nuclear fluid are very large, and we would expect the nuclear fluid droplets to keep on combining ad infinitum, in order to liberate more energy. Thus, very large and heavy nuclei would be built up. Actually, no stable nuclei have yet been observed containing more than 238 of these nuclear droplets, or nucleons.

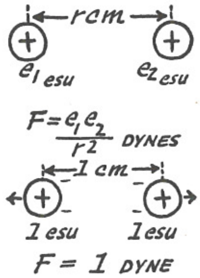

Fig. 13
Culomb's Law

The answer is simply that there is another important force which prevents the nucleons' combining indefinitely (see figure 13). This is the force of electrical repulsion between like charges, often called the "coulomb force" after the man who first set up the mathematical laws governing it. Coulomb's law is very simple. It states that the repulsion between two like charges is equal to the product of the charges divided by the square of the distance between their centers. If the charges are unlike, the force is attractive. Thus:

$$F = \frac{e_1 e_2}{r^2}$$

where F = force in dynes e_1, e_2 are the electrostatic charges of the first and second bodies in the proper units, and r is the distance in centimeters separating them. Coulomb's law tells us that when we try to bring two protons together to form a bigger nucleus, there will be a repulsion tending to keep these protons apart, since they are both positively charged and like charges repel. However, surface tension forces favor combination, so that it is possible to cause the two protons to combine.

Let us suppose we have successfully combined the two protons. Now, if we try to combine two of these double proton nuclei to form one nucleus of four protons, we will have a repulsive force four (2 x 2) times as great as we had when we tried to combine the single protons (1 x 1). Hence we see that the coulomb forces increase very rapidly as we try to make larger and larger particles. On the other hand, the surface tension attractive forces for combining small nuclei into large ones do not increase very rapidly. We saw in the previous example that we had to combine eight drops together to reduce the surface by a factor of only two. Therefore, the coulomb repulsive forces soon overtake the surface tension attractive forces, and make further fusion of nuclei impossible. When the two forces are exactly balanced, the nucleus will be extremely stable, since there is no tendency for it to break down into smaller parts because of coulomb repulsion (see figure 14), or to fuse together into larger ones because of surface tension attraction.

Obviously, this balance should occur for a nucleus of some intermediate size and it turns out to be near silver (Ag), at.wt. 108, at. no. 47, which is practically in the middle of the periodic table of elements. Theoretically, all elements which are lighter than silver should stabilize themselves by forming silver through fusion of their nuclei. Conversely, all elements heavier than silver should stabilize themselves by breaking into smaller parts, or as we say, by "fission", to form the lighter element silver. Furthermore, the farther a heavy element is situated from silver

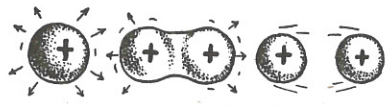

Fig. 14 Electrostatic Repulsion causes Fission of Heavy Nuclei.

in the periodic table, the more unstable it is, and the more energy can be liberated by its fission. Figure 15 shows the amounts of fission and fusion energy, which are a direct measure of instability for the various elements. The nuclear physicist uses a unit known as the *electron volt*, the conversion of which into other energy units may be found in table on p. 50. Notice that the amount of fission instability energy for uranium (U) is the highest of any natural occurring element on the chart.

One is tempted to ask what effect the neutrons in the nucleus have on its stability? We have confined our discussion to protons alone. Since the neutron has no electrical charge, we might think that it would be possible to bring a great number of neutrons into the nucleus, and increase the nuclear stability because of the surface tension forces. This supposition is true to a certain extent. With the exception of the very lightest element —hydrogen—all stable nuclei contain at least as many neutrons as protons. A good way to think of the neutrons

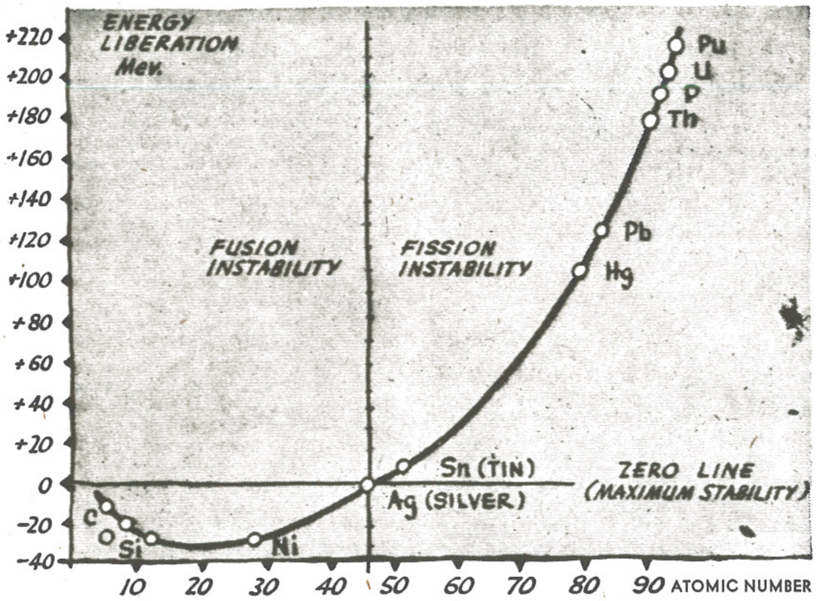

Fig. 15 Fission and Fusion Instability Energies of the Various Elements.

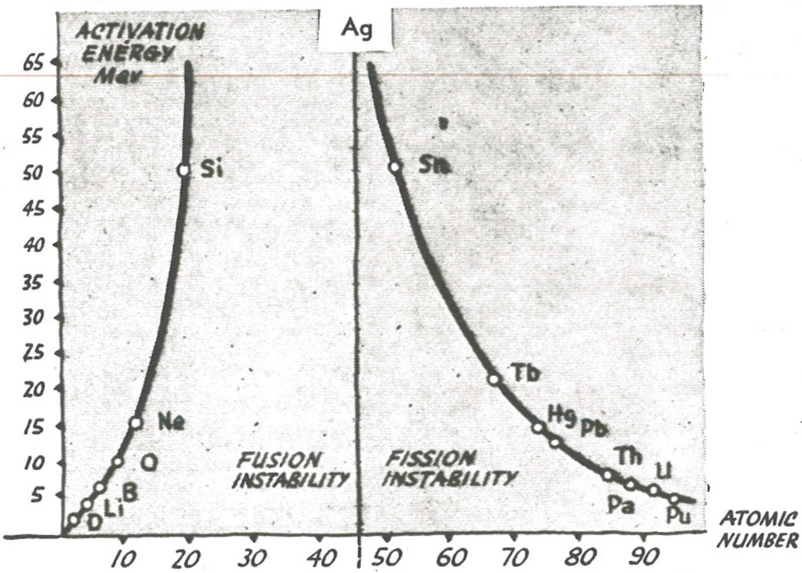

Fig. 16 Fission and Fusion Activation Energies of the Various Elements.

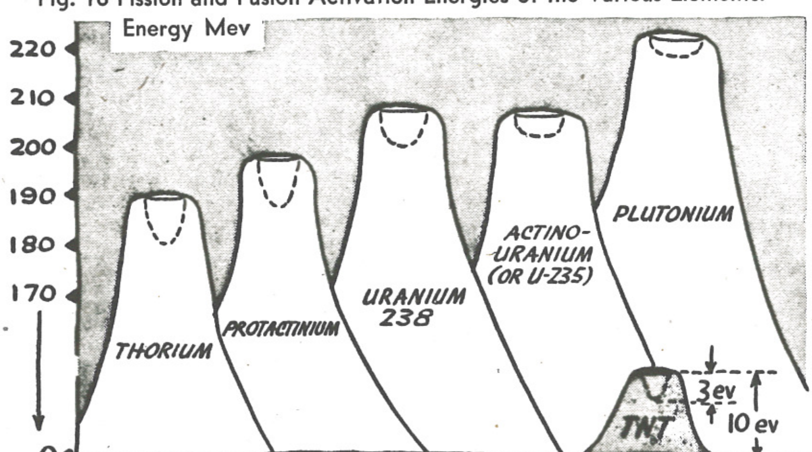

Fig. 17 Activation and Fission Instability Energies of Several Unstable Nuclei.

in the nucleus is as buffers, which keep the protons apart, so that they cannot get close enough together to upset the nuclear equilibrium and blow the nucleus apart. As we put more protons into the nucleus, their mutual repulsion increases rapidly, so that more neutrons in proportion, as well as in total number, are required. Thus for helium, carbon, oxygen, and nitrogen, the ratio of neutrons to protons is 1/1. For heavier elements the ratio increases. At the middle of the periodic table, it is about 1.3/1 for silver, and at the end of the table it is up to 1.6/1 for uranium. These n/p ratios can be shown to be the most stable arrangements for nuclei according to quantum theory, and, in fact, we shall find later on that a nucleus with too many neutrons is just as unstable as one with too few.

Activation Energy for Fusion and Fission

From our discussion about nuclear stability, fission, and fusion, the question immediately arises, "how can any of the elements except silver exist at all—why don't they all blow apart or fuse to form silver?" The answer lies in the concept of activational energy, which we discussed in the first chapter. Before we can get any nuclei to disintegrate, we must first supply a quantity of activational energy. Obviously, the easiest nucleus to attack is the one which requires the least activational energy, just as it is easier to detonate nitroglycerin, which goes off from merely jarring a bottle of it, than it is to detonate TNT, which is stable even when a rifle bullet is shot through it.

Figure 16 shows the activational energy for fission or fusion of the various nuclei. Note how low the value is for uranium. From this low activation energy, coupled with its high fission instability energy as shown in figure 15, one quickly sees that the fission of uranium presents an interesting possibility for obtaining large amounts of energy. Just how to release this energy by supplying the activational energy required is a question we will discuss in subsequent chapters. This curve, taken from the data of Bohr and Wheeler (Physical Review, Sept. 1939) represents the fission instability energy as the height of the peaks. The craters' depths are a measure of the activation energy required for fission. It is well to emphasize the difference in scale in figure 17 for the TNT explosion, a chemical reaction and the nuclear reaction. Roughly 20,000,000 times as much energy is liberated per atom of U_{235} undergoing fission as is liberated by a molecule of TNT in chemical reaction.

That difference seen even in proportion—the actual difference in figures being too great for us to really grasp—is the difference between previous man-made explosions and the atomic bomb. A whole new scale of power is involved, with completely different concept.

IV: Nuclear Transformation

RADIUM AND RADIOACTIVE DISINTEGRATION

MOST OF US have heard of the work of Pierre and Mme. Curie in the discovery and identification of radium. This work was one of the more important advances of modern physics and chemistry. Their findings were preceded by those of Becquerel during the 1890's who found that a photographic plate, when placed in proximity to ores or compounds of uranium, was affected in the same manner as if it had been exposed to light. This occurred, even when the plate was protected by sufficient paper covering to assure that even the strongest light could not affect it. Becquerel reasoned that there was something associated with uranium which produced very penetrating rays, which, although not in the visible light range, behaved similarly to light and could blacken a photographic plate. That these rays were not appreciably retarded by the usual coverings of the plate was evidence of their great penetrating power.

The Curies carried on Becquerel's work, and showed that the active material causing these rays was not uranium itself, but a hitherto undiscovered element, which occurred in very minute quantities along with the uranium. They called this new element *radium.* The reason that radium is always found with uranium in natural ores is that uranium is an unstable substance, which slowly decomposes to radium. Actually, the picture is very complicated, since uranium decomposes to a number of other unstable elements before radium is formed. And the radium also decomposes through a number of intermediate elements, until it finally forms the stable element, lead. Such a sequence of unstable elements is known as a radioactive series or "family."

There are three such families, deriving from uranium, thorium, and actinium. U_{235}, the less abundant isotope of uranium, is really not in the uranium family at all, but in the actinium. However, it occurs with uranium (U_{238}) in nature, because the chemical properties of the two isotopes are very similar. All three of the radioactive families decompose through intermediate steps to form lead, although each forms a different isotope of lead. Natural lead is a mixture of these three isotopes plus a fourth, Pb_{204}.

Now, focusing our attention on radium alone, we find that radium is decomposing at a measurable and fixed rate into another element, a heavy, chemically inactive gas known as radon. At the same time the radium is giving out certain emanations which are divisible into three distinct classes. The first, called *alpha rays* or alpha particles, consists of a number of fast moving helium ions. Recalling our picture of the helium atom —two protons, two neutrons, and two

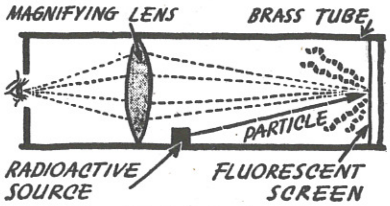

Fig. 18 Spinthariscope.

electrons—we see that an ion can be formed by stripping off one or both of the electrons. Actually, both electrons are missing, and the alpha particle is simply a helium nucleus. Alpha particles are readily detected by means of a simple instrument known as the spinthariscope. (See figure 18.)

The spinthariscope consists of a screen coated with a material such as zinc sulphide, and an eyepiece to magnify the screen. When an alpha particle strikes the screen, it causes a transformation of the zinc sulphide, which emits a little flash of light. This flash of light is magnified by the eyepiece. The same phenomenon occurs in the "radium dials" of clocks and watches. Here a small amount of radium or one of its compounds is mixed with some zinc sulphide pigment, so that alpha particles are always colliding with the molecules of ZnS, and emitting light. This emitted light can be observed when the dial is in the dark.

The alpha particles are moving with considerable velocities—between 2,000 and 20,000 miles per second, or roughly from one to ten per cent the velocity of light. Because of their high velocities, they have high kinetic energies. They are able to penetrate several cm. of air, or thin foils of metal (less than a mm.) before losing their energy. They lose a little energy each time they collide with another atom, until they are finally stopped. The energy of the collisions is dissipated, not as heat, but in knocking out the electrons from the atoms with which the alpha particle collides. By such collisions ions are formed. Thus the alpha particle leaves a number of ionized atoms in its wake, and if we are able to observe these ions, we will at least be able to tell where the alpha particle has been. Details of these observations will be given in the next section.

The second type of emanation from radium is known as *beta rays* or particles. The beta rays are nothing more than streams of fast moving electrons, which have been thrown out of the radium. They travel several hundred times farther than the alpha particles, either in air or metal, before coming to a stand-still. This is logical, since the mass of the alpha particle—two protons plus two neutrons—is approximately 7500 times greater than that of the beta particle. Thus a beta particle, with the same energy as an alpha particle, will move much faster than the alpha particle, and go farther before its velocity is brought to zero by collisions with the atoms which it ionizes. Evidently then, it will not ionize as many atoms for a given length along its path as will the alpha particle, if their energies, and hence the number of ions which they can form, are equal. Although the energies of the alpha and beta particles are not exactly equal, they are of the same order of magnitude, so that our conclusions are valid.

The third type of emanation from radium, known as *gamma rays,* does not consist of particles at all. It behaves very much like light, or better, like X-rays of very high frequency. Gamma rays move at the speed of light and with wave motion. They differ from light only in having a much higher frequency; or putting it another way, their wave length is much shorter. In fact, this is the main distinction between different types of electromagnetic radiations, including radio waves, radar, radiant heat, infra-red, visible light, ultra-violet, X-rays, gamma rays, and cosmic rays. The sequence given is in order of increasing frequency and penetrating power. In order to stop gamma rays from radium, several inches of lead are required, while several feet of lead or concrete are necessary to stop those encountered in atomic bomb work. Obviously, gamma rays are very penetrating, much more so than alpha and beta rays which can be stopped by much thinner sheets of metal.

At this point let us consider the methods of detection and counting of these particles from radioactive disintegration. One of the simplest is by using the *gold leaf electroscope,* familiar to any student of elementary physics (see figure 19). When the electroscope is charged, there will be an excess of either positive or negative charges on the small sphere. These charges will distribute themselves over the sphere, the conducting rod and the two thin gold leaves which are attached to the rod. Let us suppose that the sphere is charged positively; the gold leaves also become positively charged. Because like charges repel one another, the two leaves will tend to move apart. This

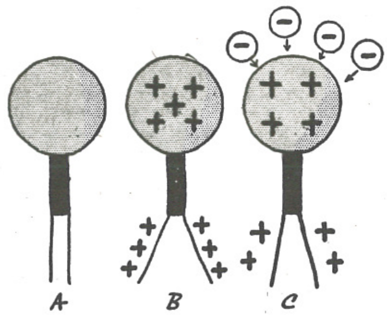

Fig. 19 Gold Leaf Electroscope (a) uncharged (b) charged (c) neutralization of charge.

they can do easily, since they are very thin and light, and only a small force is needed to overcome their inertia.

If ions are produced in the neighborhood of the small sphere, negative ions will be attracted to the positive sphere and will neutralize its charge. The charge on the gold leaves is also lost, and the leaves then move back together. The rate with which the leaves move back together is proportional to the rate at which the charges on the sphere are being neutralized. This in turn is proportional to the rate of ion production in the neighborhood of the sphere; here the production of ions depends on the entrance of charged particles such as alpha or beta rays into the surrounding space. Gamma rays are also able to produce ions in matter through which they are traveling. Thus, the rate of motion of the gold leaves is directly related to the rate of entrance of alpha, beta, or gamma rays into the space surrounding the small sphere. By suitable refinements, it is possible to make very sensitive and accurate detecting and counting instruments based on the simple electroscope.

The Geiger Counter (figure 20) is another useful device for the detection and counting of particles from radioactive disintegration. The counter consists of two electrodes, one a metal cylinder and the other a fine metal wire inside the cylinder. The two electrodes are separated by low pressure gas, and the whole is enclosed by a glass envelope. A potential difference of 1500-2000 volts is maintained between the two electrodes. This potential is only slightly below that required for a spark discharge through the gas between the electrodes. A thin "window" in the glass permits the entrance of alpha, beta, or gamma rays into the chamber. When a particle enters the chamber, a quantity of ions is produced in the gas. Thus the gas becomes electrically conducting and a discharge occurs between the two electrodes.

This discharge causes a momentary flow of current in the external circuit. The current soon stops, however, as the external circuit is so arranged that the external voltage is reduced during the discharge. The external current may be amplified to cause a "click" in a loud speaker, to operate a mechanical register, or to cause a visual pulse on an oscilloscope screen.

The Geiger Counter is very useful for studying nuclear reactions and can be constructed with such sensitivity that a single alpha, beta, or gamma emanation may be detected and counted. By placing various screens in front of the chamber window, it is possible to filter out all particles other than the type in which the observer is interested.

Radioactive Decay

The decay of radioactive elements such as radium into other elements is an example of what is called a "statistical process," which means that the number of particles undergoing a particular process or reaction is proportional to the total number of such particles present. Such processes can also be called probability processes. A common example with which we are all familiar is the rise or fall of a population. If the excess of births over deaths in a given community is forty per thousand, then in a population of one thousand people, we expect an increase of forty in a year, while if the population is two thousand, the increase will be twice as great or eighty in a year. Another way of expressing this state of affairs would be to say that the population is doubling itself every twenty years. Similar relations can be derived if the population is decreasing, rather than increasing.

The decay of radioactive elements is analogous to a population decrease. Radium decays at such a rate that the amount of radium halves itself in about sixteen hundred years. Thus, if we start with a gram of radium, in 1600 years we will have only a half gram left. In 1600 years more, a half of that which remained will decay, and we will have only a quarter of a gram left. *We define the decay time or half life of a radioactive element as that time required for a given quantity to decompose so that only half of it remains.*

It is important to remember the following points—the decay time is independent of the amount of material present, as long as there are a large number of atoms; and the decay time has a constant value for any particular element (or isotope). The half-life varies greatly for different radioactive elements. Thus the half-life of uranium U_{238} is several billion years, while that for some of the intermediate products in its decay to radium and thence to lead, is only a millionth of a second. Obviously, an element with a large decay time or long half-life is more stable than one with a shorter half-life.

The graph in figure 21 shows the amounts of radium, starting with one gram, that remain at various times. Notice that the *total amount* of material which has changed, or the rate of change, is much higher at the top of the curve than at the bottom. Theoretically the amount of unchanged material can never fall to zero, although we can say for practical purposes, that all of the material has disappeared when the amount present is less than a measurable quantity. Later we will discuss a new element, plutonium (Pu), which was discovered in recent years as a result of the work on the atomic bomb. The half-life of Pu is only 25,000 years. Hence if there was an appreciable amount of the element present when the earth was formed several billion years ago, it would have decayed to such an extent that the amount of it present today would be negligible. Therefore for practical purposes, we can say that no Pu exists in nature.

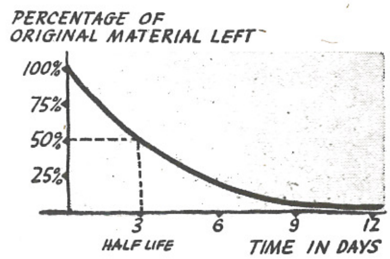

Fig. 21 Radioactive Decay Curve.

A rather unusual fact concerning the decay time of a radioactive substance is its independence of temperature, pressure, presence of catalysts, or other factors which influence chemical reactions. All evidence so far observed indicates that the decay time is absolutely constant for any particular element or isotope.

Nuclear Transformations

In the first section we said that atoms are the smallest particles which could exist and yet retain the characteristic properties of the element which they compose. We also stated that atoms cannot be destroyed by any chemical means. The decomposition of radioactive materials is therefore a new phenomenon to us, and something beyond the realm of ordinary chemical changes. For example radium (Ra) is a very heavy metal, chemically active, and in its chemical properties greatly resembles the rather common element calcium. It has an at. wt. of 226, and at. no. of 88. But radium decomposes into an entirely different element—radon (Rn), at. wt. 222, at. no. 86. Radon is a heavy gas, chem-

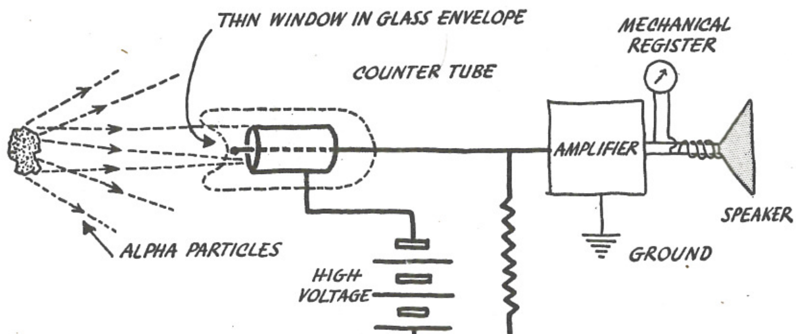

Fig. 20 Geiger Counter.

ically inert, and resembles the gas neon (Ne). Here, we have before us an example of *nuclear transformation*—one element being converted into an entirely different one. Although this transformation is initiated and carried out without our aid or control, it nevertheless presents a fascinating possibility. Since we now know that the atom is not indestructible, and that one atom can be changed to another, we visualize the possibility of converting one element to another at will, and possibly even manufacturing new elements, unheard of in nature. The alchemists' dream may come true, and we may yet be able to make gold from lead. Let us see what tools will be needed for our work.

We have two alternatives in changing the nucleus. We may attempt to increase the atomic number and mass by adding particles to it, or we may decrease them by removing particles from the nucleus. How can this be done? Not by any chemical means yet known. We must work with the ultimate nuclear particles themselves. With such ideas in mind, the physicists of forty years ago began bombarding various nuclei with alpha particles, electrons, and gamma rays from natural sources. Later they also employed other nuclear particles—protons, deuterons, and so forth—as these became available from artificial sources. (In Section VII we will discuss methods of obtaining nuclear particles artificially.)

At last, one experiment was successful, and Rutherford in 1919, found that by bombarding nitrogen with fast moving alpha particles he could produce oxygen. These alpha particles were obtained from disintegrating radium. We represent the transformation as follows—

$${}_7N^{14} + {}_2He^4 = {}_8O^{17} + {}_1H^1$$

The subscripts represent the atomic numbers or nuclear charges, and the superscripts the atomic weights. Notice that the totals on each side of the equation for both atomic numbers and atomic weights must balance. If we consult the periodic table of elements, we find that oxygen is listed with an atomic weight of only 16, while the oxygen above has an atomic weight of 17. Thus the transformation we have produces a heavy isotope of oxygen, a stable material found in small quantities (0.04%) in the ordinary oxygen of the air.

The amount of heavy oxygen produced by this reaction is very small. In fact, the amounts of material produced by any kind of nuclear transformations up to the recent atomic bomb work were very small, too small to be observed by direct weighing. The reader is then forced to ask, how did Rutherford know what he had done when he bombarded nitrogen?

The Wilson Cloud Chamber

To answer the above question we will explain the operation of one of the most useful machines known to the nuclear physicist for carrying out experiments and interpreting his results. This instrument, the Wilson

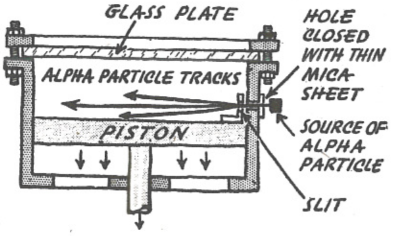

Fig. 22 Wilson Cloud Chamber

Cloud Chamber, is very simple in principle and operation (figure 22). The chamber consists of a cylinder fitted with a movable piston which encloses air or other gas. A little water in the bottom of the cylinder saturates the air with water vapor.

Now if the piston is moved downward quickly, causing an expansion of the air in the cylinder, the air will be cooled slightly. This is a phenomenon familiar to everyone who has noticed that the air rushing out of an automobile tube cools the valve through which it passes. Since the amount of water vapor which can be held in the air decreases with lowered temperature, the cooled air, which was formerly saturated, is now "supersaturated" with water—it is holding more water vapor than it should. In other words, the relative humidity is greater than 100%. However, it is possible for this water to stay in the air as vapor for a considerable time, unless there are little centers—dust particles or ions—on which it can begin to condense out. The necessity of such condensation centers, and the fact that dust or smoke particles can supply them, explain the extensive fogs which are common over such industrial cities as Pittsburgh.

Let us expand the air in the chamber by releasing the pressure on the piston. A fog forms since there are sufficient dust particles in the air of the chamber to act as condensation centers. When the fog settles, most of the dust particles fall to the top of the piston which forms the bottom of the chamber. We then compress the air and repeat the expansion process, causing additional fog formation and the settling of more dust particles. After several of these compression-expansion cycles, most of the dust particles will have been removed from the chamber air, and there will not be enough condensation centers to cause fog formation when the air is again expanded. Now, if we bring a piece of radium near the thin glass window on the side of the chamber, some of the alpha and beta particles as well as gamma rays will go through the window and will produce ions in the air. The water vapor will condense out as a fog on these ions, and if we have a transparent top to the chamber, we will readily see white fog tracks on the black background of the piston top. Thus, we have an almost direct method of observing the path of a charged particle. Notice that we say *charged* particle. Uncharged particles are unable to produce ions and cause fog; so that they cannot be directly detected in the chamber. This is important when we attempt to follow neutrons in the chamber, for neutrons are uncharged.

Inspection of the tracks which particles make in the cloud chamber gives us considerable information about their nature, and facilitates the identification of unknown particles. Figures 23 and 24 are schematic representations of cloud chamber tracks of the particles given off by decomposition of radium. The short, heavy tracks are made by alpha particles, which have a low velocity and hence travel only a short distance before dissipating their energy. The tracks are thick because a great number of ions per centimeter of path are produced by the alpha particles.

The lighter and faster moving beta particles travel farther before losing their energy, and therefore have longer tracks. Also, since they do not produce so many ions per centimeter of path length, their tracks are thinner. Notice that the tracks of both particles are practically straight lines until near the ends, where they curve appreciably. During most of their flight, the particles are moving at high velocities, and are not greatly deflected by collisions with the atoms of the gas. However, at the end of the flight, when the velocities have been

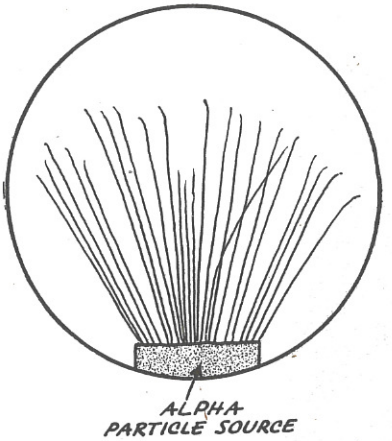

Fig. 23 Cloud Chamber Tracks of Alpha Particles.

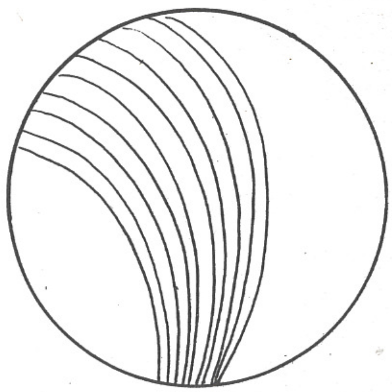

Fig. 24 Cloud Chamber Tracks of Beta Particles.

greatly reduced, further collisions are able to deflect the particles from their straight line paths.

Gamma rays also produce ions and therefore tracks in the chamber However, the mechanism by which this is done is different from that by which alpha and beta particles produce ionization, and is rather complicated. Suffice it to say that gamma rays produce many thin, irregular tracks, which are easily discernible from those of the alpha and beta particles.

We are now ready to repeat mentally Rutherford's experiment. It can be done very simply—all we need is a cloud chamber and a small source of alpha particles. See figure 25 (a). Most of the alpha particles which enter the chamber merely ionize the atoms of oxygen or nitrogen in the air; however, *once in a very great while, one alpha particle will collide head on with the nucleus of a nitrogen atom,* with the results shown pictorially in figure 25 (b). Notice that the thick track of the incoming alpha particle forks into two other tracks. The shorter, thicker track is made by the new oxygen nucleus formed, while the longer, thinner one is made by the proton. Since the proton is only 1/17th as heavy as the oxygen nucleus, it moves faster, and makes a longer and thinner track. Conversely, from measurements of the length and thickness of the two track, it is possible to identify the two particles which produce them.

In order to obtain a complete picture of the reaction, it is really necessary to take pictures of the tracks with two cameras placed at different positions, so that the correct angular relation between the incoming and exit tracks can be determined. The angles must be known in order to determine the momenta of the different particles. Since momentum is the product of mass and velocity, these two important quantities can be calculated.

We stated that only a very small number of the alpha particles are successful in producing disintegration. This is rather easy to see, when we recall that the atomic diameter is so much larger than the nuclear diameter, and we need a direct hit on the nucleus to produce the transformation. We remember that in round numbers the atomic diameter is 10^{-8} cm., and the nuclear diameter only 10^{-12} cm. The nuclear diameter is smaller by a factor of ten thousand, and since the areas of circles and spheres increase as the squares of their diameters, the nucleus presents a target which is only one hundredth millionth (1/100,000,000) as great as that of the atom as a whole. Thus an alpha particle which lands within the atom will have only one chance in a hundred million of hitting the nucleus. Looking at the problem another way, we can say that, on the average, a hundred million alpha particles will be required to hit a particular nucleus, or one alpha particle must go through a hundred million atoms before hitting a nucleus. Now the alpha particle, as we have seen, loses

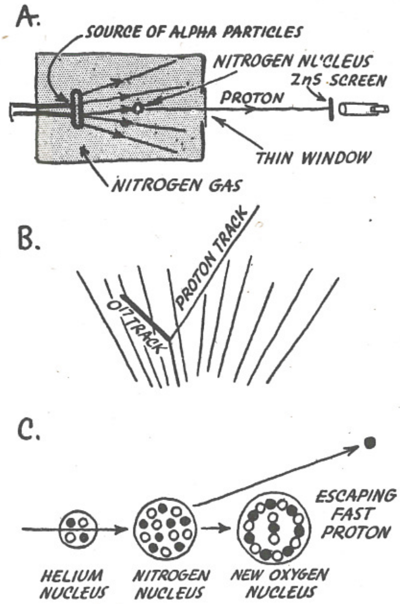

Fig. 25 Rutherford's Experiment.

(a) Simplified Representation of Apparatus (b) Simplified Representation of Cloud Chamber Photographs (c) Explanation of the Nuclear Transformation.

energy in passing through atoms and ionizing them. Before it is brought to a total standstill, an alpha particle of average energy (about one million electron volts) can ionize twenty thousand or so atoms. So dividing a hundred million by twenty thousand, we get five thousand, which is the number of alpha particles needed to assure the collision with a single nucleus. But even this figure is conservative, for there is a force which tends to prevent the collision of the alpha particle and the nucleus. This is the coulomb repulsion between the charged particle and the charged nucleus. And still a third factor enters to reduce the probability that the nucleus will disintegrate or transform, even when it is hit. The fact is that the nuclear stability may not be disturbed sufficiently by the entrance of the alpha particle to cause any change in the nucleus. The nucleus may merely throw out the alpha particle again. The physicist says that there is a "barrier energy" which must be overcome. This barrier energy is somewhat analagous to the activation energy of the water in the crater, which we discussed in Section I.

Thus there are three factors which make the probability of nuclear transformation very small. They are (1) small target area of nucleus, (2) repulsion of charged particle by charged nucleus, and (3) barrier energy which must be overcome. The combined effect of all these factors makes the probability of causing transformation about one for each hundred thousand particles used. Hence, of one hundred thousand alpha particles which are shot at the nitrogen atoms, only one is effective in causing the nitrogen to turn into oxygen, and the others are simply wasted.

Returning to our cloud chamber photographs we see that a great many photographs must be taken before one is found which shows the nuclear disintegration. In order to avoid tediousness, automatic photographs may be taken by opening the camera, just at the instant chamber has expanded. After this, the chamber must be compressed again and the fog cleared away by applying an electric charge to the walls of the chamber. The charge will neutralize the ions and draw them to the walls. The difficulty is that the time required to get the chamber ready for the entrance of the next particle is about forty times as great as the expansion time in the chamber, so that the chamber is good for observations only about two per cent of the total operating time. Recently, however, the cloud chamber has been further modified by use of vacuum tube circuits, so that a photograph will be taken only when a track is produced as a result of a nuclear transformation. The instrument may be modified so that it will respond only to a particular type of transformation. Thus, the time of the experimental observation and the amount of photographic film needed may be greatly reduced.

V: Nuclear Transformation Continued

—EQUIVALENCE OF MASS AND ENERGY

IN the previous section we learned that by the bombarding of nitrogen nuclei with high speed alpha particles, we are able to transform the nitrogen nucleus into that of an isotope of oxygen. Following this discovery by Rutherford, other physicists got busy and bombarded other elements with alpha particles of different speeds or energy contents, and with other particles as well. Recalling what we have learned in the previous sections, we can see that we have a choice of several particles. Let us list these

particles in order to obtain a composite picture of the possibilities:

Particle	*Mass*	*Charge*	*Remarks*
electron ..	zero practically	-1	Same as beta ray
positron ..	"	1	Not yet used as bombarding particles
proton ...	1	1	Same as hydrogen ion
neutron ..	1	0	Same as hydrogen atom
deuteron..	2	1	Same as heavy hydrogen ion
alpha particle ...	4	2	Same as helium ion
gamma rays ...	0	0	Not particles, but "bundles" of energy.

When these particles are used at various speeds a great number of nuclear transformations may be effected. It is not necessary for us to go into these various reactions in detail, but we can summarize them by saying that when one of the particles listed above is shot at a nucleus of a particular element or isotope, that element or isotope will increase or decrease in atomic number and/or mass number one, two, three, or four units. This may lead to the formation of an unstable intermediate substance. If the intermediate substance is radioactive, it will then emit one of the particles listed above, the emitted particle generally being different from that of the original bombarding particle. We speak of gamma rays in this sense as if they were the same as any other particles, although actually gamma rays are not particles, but waves of energy, as we have previously stated. It is important to repeat that the change in the nucleus is only a few units, either in atomic number or atomic weight. We shall later find an important exception to this statement when uranium is bombarded with neutrons. This reaction produces a much greater change in the nucleus. In fact the nucleus is practically split in two. This is the process known as "fission of uranium."

Mass Changes in Nuclear Reactions

Let us consider the reaction of lithium (Li, at. no. 3, at. wt. 7) bombarded by protons. It has been found that for each Li atom that reacts, two atoms of helium are formed. The equation is:

$$_3Li^7 + {_1H^1} = 2\ {_2He^4}$$

If instead of considering one atom of Li, we consider a gram mole of its atoms, we find some very interesting information by comparing the weights of the reactants (Li, H) and the products. Using the very accurate values of atomic weights determined by the modern mass spectrographs, we compile the following weight balance:

Mass of Li	— 7.01818 gms
" " H	— 1.00813
Total mass of reactants	8.02631
Mass of He	— 4.00389
" " "	— 4.00389
Total mass of products	8.00778 gm.

We immediately see that the two totals do not balance. In fact, there is an excess of 8.02631 minus 8.00778 = 0.01853 gm, of reactants over products. If our work has been conducted carefully and accurately, and there are no other particles which account for this mass difference, we conclude that this amount of material has been lost or destroyed. But this conclusion is a contradiction to our common sense, and to the fundamental law of physics and chemistry, that matter can neither be created nor destroyed. We had another similar law which stated that energy can neither be created nor destroyed. Now we are forced to revise our ideas somewhat. As Einstein has proved, the true state of affairs is "*The sum of matter and energy in a particular system is constant, but matter and energy are mutually interconvertible.*" Thus Einstein explained that the above mass difference was converted into a quantity of energy. In this reaction careful experiments showed that the helium atoms thrown off from the reaction were moving with a considerable velocity (about one twentieth the velocity of light), and therefore possessed a great deal of kinetic energy. Einstein has furthermore stated that a very simple relation exists between mass and energy, expressed:

$$E = mc^2 = km$$

Here E is the amount of energy in ergs, m is the mass in grams, and $k{=}c^2$ is a constant equal to 9×10^{20}. "c" itself has a value of 3×10^{10}, which is also the velocity of light in cm./sec. Thus, when 0.01853 gm. of mass disappear, the equivalent amount of energy, $(0.01853) \times (9 \times 10^{20}) = 1.67 \times 10^{19}$ ergs appears. The erg is a rather small unit of energy, so we will convert it into units with which we are more familiar. One erg = 9.48×10^{-11} btu = 7.38×10^{-8} ft. lb. = 2.77×10^{-14} kw.hr. Converting from ergs to btu, we obtain a value = 1.58×10^9 btu. If we recall that the burning of a pound of coal produces about 15,000 btu, then the burning of a ton will produce $(2000) \times (15{,}000) = 3.0 \times 10^7$ btu. Comparing this value with the 1.58×10^9 btu for the nuclear reaction, we see that the amount of energy liberated when only seven grams of Li combine with one gram of H is equivalent to that obtained from the burning of about 50 tons of coal. Remembering that there are 454 grams to the pound, we can show that the reaction with a pound of Li would be equivalent to about 3250 tons or seven million pounds of coal! This is a huge figure, but it is not unusual for nuclear reactions. In fact it is useful to remember that nuclear reactions can be much greater—even one million to one hundred million times as great as the usual chemical reactions. Ten million times is a good average figure to remember.

The conversion of mass into energy is a concept which is very new to most of us, who have always been schooled according to classical physics, and thought that mass was indestructible, and likewise energy. The inquiring reader will immediately wonder why this conversion was not previously detected. The reason is that the energy changes in the chemical reactions with which we were familiar were so much smaller than the nuclear energy changes, that the mass differences produced were not noticeable. As an example, suppose we heat a 500 gallon tank of water from its freezing point (32°F.) to its boiling point (212° F.). Since there are 8.33 pounds to the gallon of water, the amount of heat we put into the water is $(500) \times (8.33) \times (212\text{-}32) = 750{,}000$ btu. Using the conversion factor previously given for btu to ergs, we see that this is also equal to $7.5 \times 10^5 \div 9.49 \times 10^{-11} = 7.9 \times 10^{15}$ ergs. But according to the Einstein equation, one gram is equivalent to 9×10^{20} ergs; the mass equivalent of our energy input is, therefore, only $7.9 \times 10^{15} \div 9 \times 10^{20} = 0.000009$ gm. This is about one hundredth of a milligram, and a milligram is the smallest unit accurately measured on the ordinary chemical balance. With a micro balance, a mass difference of 0.000009 gm. can be distinguished in a sample totaling a few milligrams. However, it is obviously impossible to measure such a small mass (which is far less than that of an average Texas mosquito) when it is associated with that of five hundred gallons of water. It was not until the huge energy changes associated with nuclear reactions were discovered, that mass changes large enough to be detected were found.

Predicting Nuclear Reactions

From a knowledge of the energy contents of various elements and chemical compounds, the chemist is able to predict possible reactions. In general he is able to say that those reactions which liberate energy will go spontaneously, and that those which absorb energy do not go spontaneously, but require the addition of energy to make them go. Although he uses a term called "free energy," which is somewhat different from ordinary heat of reaction, we need not concern ourselves with it at present.

Of course, this sort of calculation does not predict how fast the reaction will go, nor what the yield will be, but only whether or not the reaction is possible. We can do the same thing with nuclear reactions. All we need do is write down an equation, properly balanced, and write the proper atomic masses below, as we did in the Li-H reaction. Then, if the sum of the masses of the products is less than the sum of the masses of the reactants, there will be a liberation of energy and the reaction is probable. On the other hand, if the sum of the masses of the products is greater than that of the reactants, energy must be added to cause the reaction. We re-

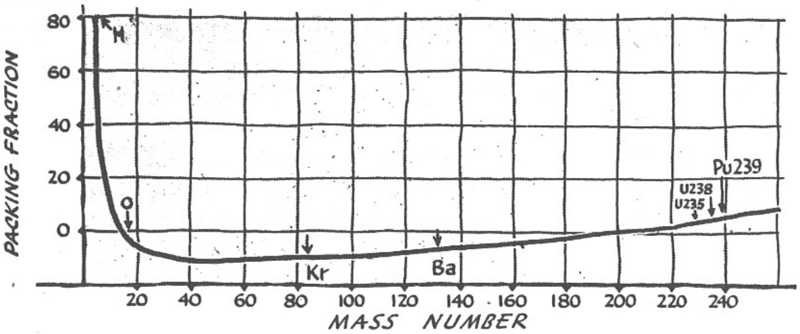

Fig. 26 Relation of Packing Fraction to Mass Number.

(CONTINUED FROM PAGE 25)

peat that the most probable reactions are those which liberate energy.

Now, since we know that all nuclei are composed of the two basic particles, the proton and neutron, in varying numbers, it is interesting to compare the mass of the nucleus with that of its component parts. If the nuclear mass is less than that of the "free" protons and neutrons which compose it, then the nucleus is stable; conversely if the nuclear mass is greater than that of its component parts, the nucleus is unstable. If the nucleus is unstable, the amount of instability energy will be directly proportional to the amount of mass excess, and it will tend to break down into more stable nuclei, or to build up into more stable nuclei, as the case may be.

The Packing Fraction

In order to have a convenient scale for measuring nuclear stability, we make use of a curve known as the *packing fraction* curve (figure 26). The curve has as its base oxygen, which has an atomic weight of 16.0000, and a *mass number* (number of protons and neutrons in the nucleus of 16). All other elements have integral mass number, but their atomic weights are either a little greater or a little less than this integral number. Thus the mass number of hydrogen is one, while its atomic weight is 1.00778. We define the packing fraction as the difference between the atomic weight and the mass number, divided by the mass number and multiplied by ten thousand. Thus for hydrogen the packing fraction is

$$\frac{1.00778 - 1.00000}{1} \times 10{,}000 = 77.8.$$

For He, atomic weight 4.00216, mass number four, the packing fraction is

$$\frac{4.00216 - 4.00000}{4} \times 10{,}000 = 5.4.$$

Notice that the packing fraction for He is considerably less than that for hydrogen, which means that He is more stable than H. We might consider as a source of energy the building of heavier He nuclei from lighter hydrogen nuclei. Let us calculate the energy which we can theoretically obtain per mole of He formed.

The He nucleus is composed of two neutrons and two protons.

Wt. of neutrons 2 (1.00897)	= 2.01794
Wt. of protons 2 (1.00778)	= 2.01556
Total wt. of nucleons	4.03350
Wt. of He nuclei	4.00216
Mass loss for reaction	0.023134 gm.

We see that for each four grams of He produced, there is a loss of 0.031 gm. Converting this mass loss to an energy production, we obtain about 2.8×10^{19} ergs or 2.7×10^{9} btu.

We have dealt at length with this particular reaction because it is probably the most important one known. This is the reaction by which the sun produces its energy. The sun is continually converting its hydrogen into helium and producing heat at the rate of 3.78×10^{33} ergs per second. This corresponds to a mass loss of nearly five million tons per second. The amount of the sun's energy which the earth receives is so small, however, that it corresponds to a mass increase of the earth of only 150 tons per day. The vastness of the sun can be realized when we consider that it is over a billion years old, and has not used up more than one-tenth the hydrogen which it had a billion years ago.

Lest the reader become overenthusiastic about the possibilities of producing energy by nuclear reactions, we must repeat that such calculations which we have just carried out for the hydrogen-helium conversion show only the possibility of the reaction, not the speed or conditions under which it will take place.

Actually it is necessary to maintain a temperature of about twenty million degrees, as exists in the sun's interior, in order for this reaction to occur. Neither is the reaction as simple as we have supposed it, but goes in a complex, step-wise manner, involving several intermediate, unstable elements. A possible explanation of this complicated reaction is given by figure 27.

Thermonuclear Reactions

We may predict the direction or possibility of a given reaction's occuring as we have just seen, merely from correct values of the masses of the elements involved. However, the rates of such reactions, even as those for chemical reactions, are influenced by the activation energies for the reactions. The concept of activation energy was discussed in Section I. If the activation energy of a reaction is high, a high temperature is required to make the reaction go; conversely, low temperatures are sufficient to initiate low activation energy reactions. The effect of temperature can be seen by considering figure 28. The accompanying curves, known as Maxwell distribution curves, give at any temperature the number of atoms possessing given energy values.

In the first section, when we discussed kinetic theory of gases we assumed that all of the molecules of a gas are moving at the same velocity and have the same energy. This assumption is not true. Actually a small number have very low energies, and a small number much higher energies than the average. It is only those molecules (or in the case of nuclear reactions-atoms) which have energies above a certain value in excess of the average, that are able to react. This excess above the average energy is the same as the term we have called the activation energy. As we increase the temperature of the mass of the substance, all of the molecules or atoms are speeded up and their energies increased. We then have more molecules which possess energies in excess of the required activational energy and are thus able to react. Therefore, the reaction rate increases with temperature. With ordinary chemical reactions, the activation energies are of the order of 10,000-40,000 calories per mole and chemical reaction rates usually double for each ten degree rise in temperature.

Referring to Figure 28 we see that at the low temperature there are N_1

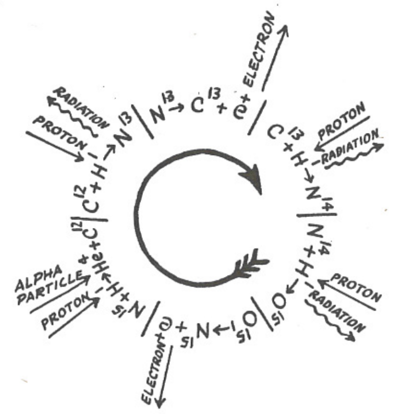

Fig. 27 The Carbon Cycle by Which the Sun Produces Its Energy.

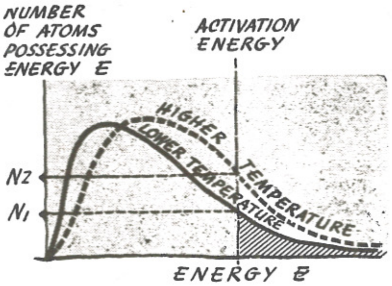

Fig. 28 Maxwell Distribution Curves for Atoms at Different Temperatures.

atoms having an energy equal to the activational energy. All atoms having this energy or a higher energy (those atoms to the right of the dashed vertical line) are then able to react. The total number of such high energy atoms is represented by the area between the low temperature curve and the horizontal axis. At higher temperature it will be noticed that an additional number of atoms are available; thus the area between the high temperature curve and the horizontal axis is about twice that between the axis and the low temperature curve, and the reaction will be about twice as fast.

However, for nuclear reactions, the activational energies are of the order of millions of calories, and the temperature effect is much more pronounced. Thus it is necessary to resort to much higher temperatures to cause the nuclear reactions to take place at appreciable rates. These temperatures are so high that nuclear reactions initiated by purely thermal

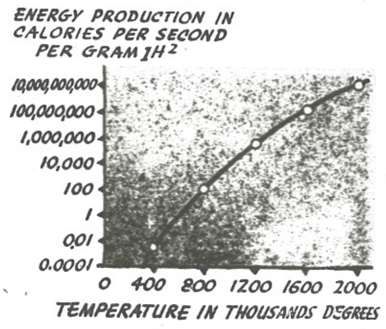

Fig. 29 Effect of Temperature on Thermonuclear Reactions.

means are impracticable in most cases. Usually we must resort to fast-moving nuclear particles for accomplishing our task. Figure 29 shows the effect of temperature on a typical nuclear reaction.

Nuclear Fission

In figure 26, one notices that the packing fraction decreases as we increase the mass number—from a high value at hydrogen to minimum values for intermediate mass numbers. It then increases again as we reach the high end of the periodic table. Since the minimum values of the packing fraction indicate increased stability, we see that *light* elements of low mass number can be stabilized by *fusion* to form elements in the middle of the periodic table. Likewise, *heavy* elements can be stabilized by *fission* into elements in the middle of the table. The atomic bomb utilizes the latter principle. Notice that the packing fraction of uranium is the highest of the natural elements on the heavy end of the table; thus it will be the most unstable element in respect to fission. Fortunately, its activational energy is very low, so that the fission of uranium is not only theoretically possible, but also highly probable. U_{235} has an even higher instability and lower activation energy, than does U_{238}, the abundant isotope. It is for this reason that U_{235} is the material we are mainly interested in for utilization of atomic energy—either for military or peacetime purposes. We will discuss later a new element, plutonium (Pu) which is also attractive from this standpoint.

SUMMARY OF REACTION TYPES

Reaction Type	Normal Mass Change	Dependence on Energy of Projectile	Yield	Type of Radioactivity Usually Produced	Sample Reactions
n capture	Positive	Resonance	Virtually 100%	Electron	$Ag^{107} + n \rightarrow Ag^{108}$ $Br^{79} + n \rightarrow Br^{80}$
np	Slightly positive	Smooth	Large for light elements; escaping barrier to consider	Electron	$N^{14} + n \rightarrow C^{14} + H^1$ $S^{32} + n \rightarrow P^{32} + H^1$
n α	Slightly positive in light elements; negative in heavy	Smooth	As above	Electron	$F^{19} + n \rightarrow N^{16} + He^4$ $Al^{27} + n \rightarrow Na^{24} + He^4$
n, 2n	Very negative	Smooth	Small	Positron	$N^{14} + n \rightarrow N^{13} + 2n$ $P^{31} + n \rightarrow P^{30} + 2n$
p capture	Positive	Resonance	Large	Positron	$C^{12} + H^1 \rightarrow N^{13}$ $F^{19} + H^1 \rightarrow Ne^{20}$
pn	Negative	Threshold: smooth increasing with energy	Large	Positron	$B^{11} + H^1 \rightarrow C^{11} + n$ $O^{18} + H^1 \rightarrow F^{18} + n$
p α	Slightly positive in light elements; negative in heavy	Smooth, increasing with proton energy	Large	Generally stable products	$F^{19} + H^1 \rightarrow O^{16} + He^4$ $Al^{27} + H^1 \rightarrow Mg^{24} + He^4$
pd	Very negative	Smooth as above	Small	Only one case established	$Be^9 + H^1 \rightarrow Be^8 + H^2$
αn	Slightly negative in light elements; positive in heavy	Smooth	Large for elements where barrier penetration is easy	Positron	$B^{10} + He^4 \rightarrow N^{13} + n$ $Al^{27} + He^4 \rightarrow P^{30} + n$
αp	Slightly positive except some light elements	Smooth	As above	Generally stable products	$Al^{27} + He^4 \rightarrow Si^{30} + H^1$ $N^{14} + He^4 \rightarrow O^{17} + H^1$
dp	Always positive	Smooth	As above	Electron	$Na^{23} + H^2 \rightarrow Na^{24} + H^1$ $P^{31} + H^2 \rightarrow P^{32} + H^1$
dn	As above	Smooth	As above	Positron	$C^{12} + H^2 \rightarrow N^{13} + H^1$ $Be^9 + H^2 \rightarrow B^{10} + H^1$
d α	Always positive	Smooth	As above	Generally stable products	$O^{16} + H^2 \rightarrow N^{14} + He^4$ $Al^{27} + H^2 \rightarrow Mg^{25} + He^4$
γn	Always negative	Sharp threshold	Small	Positron	$Be^9 + \gamma \rightarrow Be^8 + n$ $Br^{81} + \gamma \rightarrow Br^{80} + n$
γp	As above	As above	As above	Only observed for deuteron	$H^2 + \gamma \rightarrow n + H^1$

VIII: Fission of Uranium

THE MANHATTAN DISTRICT

Nuclear Bombardment With Neutrons

IN SECTIONS IV-VI we saw how the various nuclear particles—alpha particles, protons, deuterons—may be used as "bullets" for bombarding atomic nuclei to produce transmutions. We saw that one of the main difficulties in hitting the nucleus is the electrical repulsion between the positively charged nucleus and the positively charged bombarding particle. However, we could avoid this difficulty by using a stream of neutrons as the bombarding particles, and we should expect neutrons to be very effective bullets for nuclear transformations. This is actually the case. However, we are seriously limited in our use of neutrons by the fact that we do not have any natural source of neutrons available. We have shown that we can produce streams of protons, deuterons, and alpha particles in considerable quantities, by merely ionizing hydrogen, deuterium, or helium. However, to obtain neutrons we must rely on some other nuclear reaction, such as that between alpha particles and beryllium or between deuterons and deuterium.

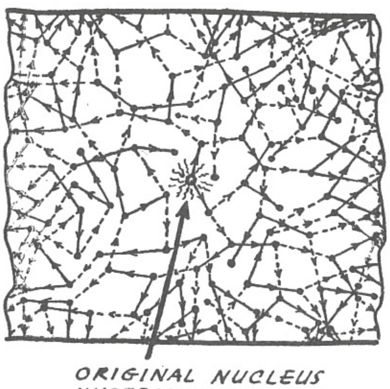

Fig. 35 Production of Neutrons by a Branching Chain Reaction.

Since these reactions themselves are slowed by the electrical repulsion between the nuclei and bombarding particles, we are back where we started.

Suppose, however, that we were able to find a reaction initiated by bombarding neutrons and giving neutrons as a reaction product. If the reaction gave only one neutron for each atom which reacted, it would continue at a fixed rate until all the material in the reacting mass had been used up. But if the reaction gave more than one, say two, neutrons for each reacting atom, then after the first atom had reacted, we would have two available neutrons. These could then react with two more atoms, to produce four reactions; these four reacting atoms would give eight neutrons, and so on. Thus the reaction rate would increase very rapidly. If the energy of such a reaction were being produced faster than it could be dissipated to its surroundings, we would have an explosion.

A reaction such as we have postulated is known as a "branching chain reaction" of which we have many examples in chemistry. The addition of an electric spark to a mixture of hydrogen and oxygen gases supplies sufficient activation energy to cause the reaction of a few atoms in the neighborhood of the spark. These atoms, combining to form H_2O, generate heat, and this heat is absorbed by more atoms to satisfy their activational energy requirements, causing them to combine, and so on. Thus the entire hydrogen-oxygen mass quickly reacts. It the gases are confined so that they build up a pressure and cannot otherwise dissipate their energy, an explosion results. We shall see shortly that such a branching chain reaction is not only possible, but actually occurs in the decomposition of uranium nuclei under certain conditions.

Uranium Fission

If the reader will scan over the various examples of nuclear reactions which he studied in the fifth and sixth sections, he will notice that in no case was any particle heavier than an alpha particle emitted from the nucleus. During the 1930's various workers in the field of nuclear physics bombarded uranium with neutrons and found that tremendous energies were given off by the reaction. The energy output was of the order of 200 Mev per nucleus reacting, while the usual nuclear reactions involved energy changes of only a few Mev, usually less than ten. Such huge energy outputs prompted considerable research, as physicists were naturally interested in obtaining these great amounts of energy in sufficient quantities to be practical in industry. At this time the exact nature of the reaction was not known, since the actual amount of reacting material was too small to be weighed or efficiently investigated.

Various theories were propounded as to the products of the reaction, the prevailing theory being that the neutron had been captured by the uranium nucleus to yield elements of higher atomic number than uranium. In fact, if one looks at the periodic chemical tables published during the late '30s, he will notice the presence of elements No. 93, 94, etc. The exact nature of the process was revealed by the German scientists, Hahn and Strassmann. By use of tracer chemistry, they showed that the uranium was producing barium, krypton, and several other elements in the middle of the periodic table. These elements have about half the atomic weight of uranium. Dr. Lise Meitner then postulated that these materials were formed by the splitting of the uranium nucleus into two approximately equal parts. Here was the first example of *fission* of a heavy nucleus. Subsequent work has shown that the fission of uranium also produces several neutrons. The exact number of neutrons produced per fission can not be revealed for security reasons. It can be assumed to be between two and three on the average. In our future discussions we will consider the number to be two for simplicity.

A word here about tracer chemistry, which is a very useful tool both to the physicist and to the biologist. Suppose we attempt to identify the products of the uranium-neutron reaction. Let us mix the small amount of the products with a quantity of a barium salt solution in water, and then precipitate the barium by addition of a sulphate to the solution. The barium will be precipitated as the insoluble barium sulphate. It will be found that the radioactivity associated with the unknown

material is in the precipitate and not in the remaining solution. This suggests that the unknown material was itself a radioactive form of barium, and because of its similarity to barium in chemical properties, it precipitated with the normal barium. If we use materials which give precipitates of silver, zinc or copper instead of barium, we find no radioactivity in the precipitates, and thus the unknown product does not contain these elements. By such experiments as these Hahn was able to identify the materials which were produced by the action of neutrons on uranium.

It will be useful for us to investigate more closely the mechanism of uranium fission. If we look again at figure 16, which gives the activational energies for fission of the various elements, we see that the values are rather high until we reach the very heavy elements of the periodic table. Thus an activation energy of about 50 Mev must be supplied for the fission of tin. Since this is a much higher energy than that of any neutrons which we can obtain at present, we cannot expect tin to be fissionable by neutrons. As we go up the table, to terbium (Tb) for instance, we find an activational energy of about 20 Mev. But even if we were able to produce 20 Mev neutrons, we would not have a self-sustaining fission reaction in Tb because the fission does not produce more neutrons of this energy. The neutrons produced by fission of Tb have energies of only one to two Mev.

When we reach thorium and U_{238}, we see that the activational energies are even lower, only about 5 Mev, and we find that it is possible to produce fission with neutrons of only one Mev energy. This is possible because neutrons need not possess energies as high as the activational energy in order to penetrate the potential energy barrier of the nucleus. According to the quantum theory, as postulated by Gamow et. al., there is a certain probability of less energetic neutrons "leaking" through the energy barrier and getting into the nucleus. This probability increases from a very small value for low energy neutrons to a value of 100% for those having energies as high as the fission activational energy. This concept of barrier leakage is rather difficult to understand, but we must ask the reader to accept it on faith, and leave the job of explaining it to the quantum mechanics workers. Figure 36 illustrates the effect of incoming neutron velocity on barrier penetration and leakage.

Thus when we come to thorium we find that neutrons of only one Mev energy are able to produce fission of the thorium nucleus. In fact, of every twenty five neutrons which get inside the thorium nucleus, about one will cause fission. The other twenty-four are kicked out of the nucleus again, at a lower energy than that with which they entered. This is because the activation energy for re-emission of the neutron is less than that for fission of the nucleus, so that the re-emission process is more likely to occur than is

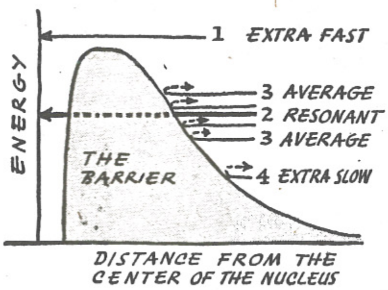

Fig. 36 Energy Barrier and Barrier Leakage Effect.

(1) Extra fast, all of these particles penetrate, (2) Resonant particle leaks through barrier, (3) Average, most of these cannot penerate barrier, (4) Extra slow, does not penetrate barrier.

fission. The reason that the re-emitted neutron is less energetic than the entering one is that it has distributed a considerable amount of its energy to the other particles in the nucleus, causing them to vibrate until they have dissipated this normal energy by emission of gamma rays, and returned to their normal state. The neutron before leaking through the barrier need have only a slightly larger amount of energy than that required for re-emission. This value for re-emission is about 5 Mev for all nuclei. In leaking through the barrier the neutron uses up 5 Mev and then has practically no energy left.

When we reach U_{238}, the activational energy for fission is still less, and of every five neutrons getting into the nucleus, one is able to produce fission. This is still not good enough to give us a self-sustaining reaction. Each fission gives two more neutrons, so that we have received only two neutrons for the five we put in. But for U_{235}, the rarer isotope of uranium, the fission activational energy is less than five Mev (the re-emission activational energy), and fission is more probable than re-emission of the neutron. We now have a probability of better than one out of two neutrons producing fission, and since each nucleus undergoing fission gives rise to two more neutrons, we will get out more neutrons than we put in, and a self-sustaining reaction is possible. With the elements neptunium(Np) and plutonium(Pu), which we shall discuss later, the same situation holds, and fission by a self-sustaining chain reaction is possible. We shall see that Pu is satifactory as a source of the chain reaction, but that Np cannot be used because of practical difficulties, the chief one of which is its short half-life.

We have mentioned U_{235} and U_{238} in the above paragraph. These are two isotopes of uranium. In any natural source the heavier U_{238} composes about 99.3% of the total, and the lighter U_{235} about 0.7% of the total. There is a third isotope, U_{234}, but its proportion is less than 0.1% and we will not be concerned with it. Work subsequent to that of Hahn, Meitner, et. al. showed that fission of uranium by neutrons was mainly fission of U_{235}, and that the effect of U_{238} was mainly as a diluent, or something which slowed down the reaction.

We can understand this diluting action of the U_{238} by recalling that we get out only two neutrons for every five we put in. Since the amount of U_{238} is about 140 times as great as that of U_{235}, it is very probable that most of the neutrons given off by the fissioning U_{235} will be captured by the U_{238} rather than by more U_{235}, and these will mainly be lost. Thus we cannot produce a self-sustaining chain reaction in a natural source of uranium, although we can easily do so in pure U_{235}, and possibly in a material which contains more U_{235} than a natural source, that is an "enriched" source.

We have now reached in our discussion the state of affairs existing in 1939, when Professor Einstein wrote to President Roosevelt suggesting that intensive research work be carried on to investigate the possibilities of using the fission of U_{235} in a branching chain reaction as a source of energy for military applications. Subsequently the Manhattan District was organized with plants at Oak Ridge, Tennessee, and laboratories at many educational institutions throughout the country. One of the more important of these laboratories was the so-called "Metallurgical Laboratory" at the University of Chicago.

Work of the Manhattan District

Let us now briefly restate the problem which faced the Manhattan District. We know that uranium is fissionable by neutrons, with the liberation of tremendous quantities of energy. We also know that if this energy can be liberated in a very short time, we can produce a powerful explosion of great military value. But this explosion will only be possible if we are able to split uranium in a branching chain reaction. Such a branching chain reaction is possible in pure U_{235}, or an enriched uranium source, but not in natural sources containing both U_{235} and U_{238}. The problem, then, is to find a way of enriching natural uranium sources, so as to give a relatively pure source of U_{235}.

The obvious solution to the problem is to separate the two isotopes of uranium, since we can then have our pure source of U_{235}. However, this separation is a difficult task. We have already learned that isotopes have identical chemical properties, and thus cannot be separated by chemical means. We will have to resort to physical methods of separation, which will be difficult and tedious because of the slight differences in the atomic weights of the isotopes, 235 and 238. Several different methods of separation were investigated, both from theoretical and practical aspects, and two of these methods were put into large scale application. We shall briefly discuss these various methods. The two methods which were finally put into operation required the fabrication of large industrial plants.

A. Centrifuge Method

The centrifuge separation employs a principle with which we are all familiar. A common example is the separation of the lighter cream from the heavier bulk of the milk. Its principle is merely that liquids or gases of different densities, under the influence of gravity or a force similar to it, will "settle out" into layers corresponding to their densities. With gravity alone, the settling is usually very slow, so that a centrifuge is employed to speed up the process. The centrifugal force is the force on a particle moving in a circular or other curved path, and tending to throw the particle out from the center. The force is directly proportional to the mass of the particle and to the square of its velocity, and inversely proportional to the radius of the circular path in which it is moving. It will therefore tend to throw out heavy (dense) particles farther than light ones, and thus will accomplish a separation according to densities, just as gravity does by settling. Since the force increases rapidly with the velocity of the moving particle, this means that the rotors of the centrifuge should be moving very rapidly, and they should be of small diameter or radius, since the centrifugal force increases when the radius decreases. By use of high speed centrifuges, it is possible to obtain forces more than a million times stronger than those of gravity.

The centrifugal force on particles moving with a given speed along a path of given radius is proportional to their mass. Therefore the difference in the force for two particles of different masses will be proportional to their mass differences, or to the difference in densities for the bulk materials. This is not in contradiction to anything we already know. We know that it is much easier to separate oil (density 0.8 gms./cc) from water (1.00 gms./cc), than it is to separate milk (1.03) from cream (0.97). Since gas densities are so much less than liquid densities, the differences in densities between gases are very small, and very great centrifugal forces are needed. Furthermore, the continuous, rapid motion of gaseous molecules in all directions hinders the separation and necessitates the use of very complicated and expensive equipment.

For separation of the uranium isotopes, the uranium was converted into the compounds $U^{235}F_6$, and $U^{238}F_6$, of molecular weights 339 and 342. Although the fluoride, because of its chemical activity, is a difficult material to handle, it is one of the few compounds which is theoretically suitable. Its virtue lies in the fact that fluorine is one of the few elements which have no stable isotopes, only the normal F^{19} is stable. The ratio of densities of gases is proportional to the ratio of their molecular weights, and the size of this ratio is a measure of the ease of separation. Thus the ratio for the two fluorides of U_{238} and U_{235} is $342/339 = 1.009$. This is not a very large ratio. In fact, if the ratio were 1.0000, no separation would be possible. Compare this ratio with that for oil and water, $1.00/0.80 = 1.250$.

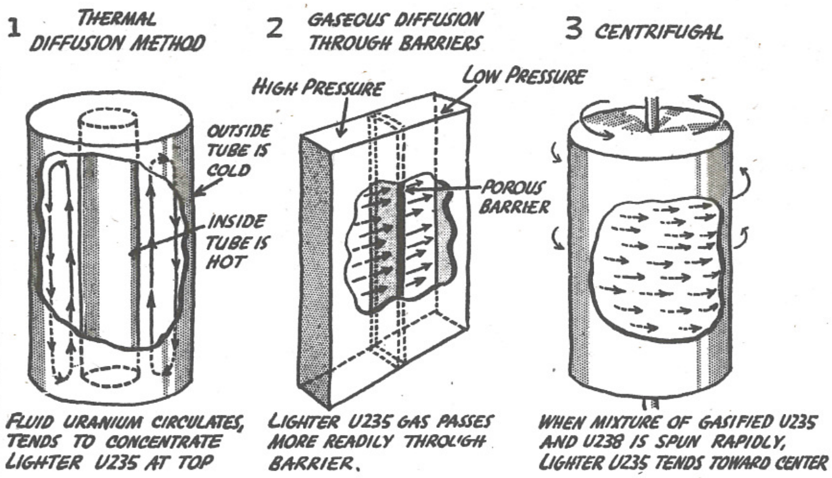

Fig. 37 Three Methods for Separation of Uranium Isotopes.

The low separation factor indicates to us that the separation will be difficult. Observations and calculations made by the workers in the Manhattan Project indicated that to produce only one kilogram (2.2 lbs.) per day of U_{235} would require 22,000 separately driven, high-speed centrifuges. These figures are quite impractical, and thus the centrifuge method of separation was abandoned.

B. Diffusion Methods of Separation

The principle of diffusion methods of separation takes us back to the kinetic theory of gases. We recall that all of the molecules of a gas at a given temperature have the same average kinetic energy. This kinetic energy is equal to one half the product of the molecular mass and the square of its velocity. Thus for molecules of varying mass at the same temperature, we may write

$$E_1 = E_2$$

$$\frac{1}{2} m_1 v_1^2 = \frac{1}{2} m_2 v_2^2$$

$$\frac{m_1}{m_2} = \frac{v_2^2}{v_1^2} \text{ or } \frac{v_1}{v_2} = \sqrt{\frac{m_2}{m_1}}.$$

Thus the molecular velocities of the different gases at the same temperature are inversely proportional to the square root of their molecular weights. The rate with which the molecules, in the gaseous state, diffuse through a porous membrane is proportional to their absolute molecular velocities. This means that if a quantity of a gas containing light and heavy molecules is allowed to diffuse into an evacuated space through a porous membrane, the light molecules will move through more quickly than the heavy ones. That part which goes through the membrane will then have a greater proportion of the lighter, fast moving molecules, and that part remaining behind will have a greater proportion of the heavier, slowly moving ones.

The ratio of the molecular velocities will be a measure of the ease of separation, and a low separation factor means that many stages, or individual membranes must be used to effect any appreciable differences in concentration. This ratio will be $\sqrt{\frac{342}{339}} = 1.0044$, which is even smaller than the separation factor for centrifuging. The factor of 1.0044 is a theoretical factor to be used for a process which does very little actual separation. In other words it is only for the first small fraction of the gas which comes through the barrier. If any appreciable material is to be gathered, the factor falls off. It will naturally be 1.0000 if all of the material goes through the membrane, since there will then be no separation. We might take 1.003 as a working factor.

Despite this low separation factor, the gaseous diffusion process proved the best process for large scale production of U_{235}.

Many practical difficulties had to be solved, and a few may be mentioned here.

The material UF_6, is a "bad actor." Upon contact with traces of water vapor it forms the very corrosive hydrofluoric acid. In addition it is a solid at room temperatures, and presents difficulties of "freezing" in the lines, etc. Thus the handling of UF_6 presents many engineering problems.

Because of the small enrichment factor of the diffusion separation, large quantities of gas and large areas of barrier or membrane material are required. This means a great deal of equipment is necessary. The problem of recycling the gas through the stages must also be considered. If we suppose that we push only one half of the gas from any one stage to the next forward stage, the gas which did not go forward, must be sent back to one of the previous stages. It cannot be discarded as it contains a greater

proportion of U_{235} than the original gas to the first separation stage. This means that the quantities of gas being handled decrease as we go along the process to the final stage, so that for only a small output from the unit, there will be huge gas volumes to handle in the early stages. Thus large compressors will be required for the early stages, and large areas of porous membrane or barrier material. The volume of gas circulating throughout the system at any time is about 100,000 times the output from the final stage.

Obtaining suitable barrier material was one of the biggest problems. In order for the barrier to work efficiently the diameter of the holes in it must be no more than one tenth that of the free path of the molecule. We have previously said that the free path is about 10^{-5} cm. Thus the holes must be 10^{-6} cm. or four ten millionths of an inch in diameter. Furthermore, these holes must not be plugged by dust particles in the gas stream, or by corrosive effects of the gas. Since the diameter, and therefore the area of the holes, is so small, a great number of them per unit area is required to get any throughput in the unit, without using exceedingly high pressures to force the gas through. The actual pressures used in the plant correspond to about one atmosphere differential between the two sides of the barrier, and the barrier must have sufficient mechanical strength to withstand this pressure differential.

Another great difficulty in operation of this plant, which is the one used for production of U_{235} at Oak Ridge, is the need for supplying adequate protection to personnel against the harmful radiations from the radioactive decay of both U_{235} and U_{238}. Of the two, the U_{235} has the shorter half-life, about a half billion years, compared to about five billion years for U_{238}. Thus it gives more radiation for a given weight in a given time. However, the U_{238} is present in much larger quantities, so that the two isotopes are about equally dangerous physiologically. The fact that there are large quantities of the radioactive materials present means that a great number of very penetrating beta and gamma rays are continually being given out; therefore thick concrete walls are necessary to shield the operating personnel. Actually, the amount of operating personnel in the plant is very small, since the plant is operated almost completely by automatically controlled instruments.

The entire plant is shaped like a large U, with materials flowing into the plant at one end of the U, and out of the plant at the other. This large U is composed of smaller ones through which the material flows in similar manner to the flow in the main U. Although the structure consists of six floors, there are no personnel on any floor but the top, and here their main job is only to make the rounds and read the instruments assembled along the walls of this floor. The actual operation of the plant is controlled by a small group of men in a master control room outside the main plant. The number of instruments for the recording and controlling of temperatures, pressures, flow rates, and so on in this plant is very large. According to a well known authority, this number exceeds the number put into all other new industrial plants in the country during the war.

C. Thermal Diffusion Methods

The principle of separation by thermal diffusion is not easy to understand. When a mixture of isotopes, in either a liquid or gaseous state, is placed in a chamber having cold walls with a hot tube or wire down its center, there is a tendency for the lighter molecules to diffuse to the interior, and the heavier ones to the exterior. Considerable work was done in the study of separation by thermal diffusion in liquids by Drs. Gunn and Abelson and their co-workers at the Naval Research Laboratory. Other groups investigated separation in gases by thermal diffusion. These processes were found to be possible ones for the separation of isotopes of uranium, but were not as practical as the gaseous diffusion method, and were not put into large scale production.

D. Electromagnetic Methods of Separation

The principle of the electromagnetic methods of separation of the isotopes is the same as that of the Mass Spectrograph previously described. This work was mainly carried on by A. O. Nier, at the University of Minnesota, and by E. O. Lawrence at the University of California. The chief difficulties of the electromagnetic method are (1) the difficulty of producing positively charged ions in the desired quantities; (2) the limited fraction of these ions used; and (3) effect of space charge. Only a small fraction of the ions produced are used, since the slits added to the machine to narrow the beam, cause those ions outside the slit openings to be rejected. Space charge effects enter if we try to use too concentrated an ion beam. Then the individual ions repel one another because of their like charges and tend to spread out the beam. In order to attain efficient separation, a thin, well focussed beam is necessary. This need not be as sharp as the beam used by Aston and Nier for the determination of exact atomic weights, and relative isotope abundance; neverthless, focussing must be sufficient to obtain a relatively pure product.

The first experimental work with the mass spectrograph for the separation of the uranium isotopes was done by Nier and his co-workers, who were able to obtain only one microgram of pure U_{235} per sixteen hour day. This was, of course, too small an amount to be practical for making an atomic bomb, but the quantities obtained by Nier were used in early research work on the properties of U_{235}, and showed that it was the isotope which was readily fissionable. In order to make larger quantities of the pure U_{235} for further investigations, Lawrence et. al. perfected the "Calutron." This machine utilized the giant magnet which had originally been intended for the giant cyclotron at Berkeley, Cal. This magnet has pole pieces 184 inches in diameter, and the air gap between poles is 72″. The Calutron solved the three difficulties mentioned in the preceeding paragraph. The third difficulty, that of space charge effects, was largely eliminated by the ionization of the residual gas in the chamber through which the ionic beams travelled. This large quantity of positive ions in the chamber tends to prevent the ions in the beam spreading out from one another and broadening the beam. The details of this improvement, as well as the methods by which the other two difficulties were solved, have not been made public. In the "Smyth Report on Atomic Energy" it is mentioned that the capacity of the Calutron was increased considerably by having more than one beam at a time in operation in the magnetic field; but again the method of doing this is not described.

It is known that several Calutrons were set up and operated, but their capacity was probably not more than a few grams of pure U_{235} per day. Apparently the main value of the Calutrons was in the production of small quantities of pure U_{235} for investigation and research, while the mass production was accomplished by means of the gaseous diffusion plant. Several other magnetic separation methods were investigated—the Isotron, Magnetron, and Ionic Centifuge. Little has been revealed about them, but it is probable that they were not found as practicable as the Calutron, although the isotron, at least, was proved workable. These methods are only mentioned in passing so that the reader will recognize the terms if he again hears of them.

Summary of the Uranium Production Problem

In this section we have shown that the discovery of the fission of uranium by neutrons, and the simultaneous liberation of great quantities of energy spurred nuclear physicists to seek a self-sustaining reaction which would liberate this energy in large quantities. Separation of the isotopes of uranium from natural sources showed that the active material in the fission was not the more abundant U_{238} but the less abundant U_{235}. In order for the reaction to be self-sustaining by means of a branching chain reaction it is necessary to have either pure U_{235}, or at least material containing a much higher percentage of it than do natural sources. Thus methods had to be worked out for the separation of the isotopes. Because chemical means are not effective, physical methods, depending on only slight differences in mass or molecular velocity must be employed. Centrifuging and thermal diffusion methods in liquids and gases were not found practical for large scale operation. After the solution of

many unusual and difficult production problems, gaseous diffusion through porous membranes was found to be the best method for large scale production.

Electromagnetic methods including the Calutron, Isotron, and Ionic Centrifuge were satisfactory for the production of small quantities of very pure materials, and were used mainly for research and investigation purposes. Of these, only the Calutron showed real promise, and the others were abandoned. Calutrons operate on the same principle as the mass spectrograph, but have a much greater output because of larger units used, which permit the use of stronger magnetic fields.

IX: Slow Neutron Reactions

PLUTONIUM PRODUCTION. THE HANFORD PLANT

IN SECTION VIII we discussed the possibilities of obtaining a neutron branching chain reaction with various elements at the heavy end of the periodic table. We saw that only with U_{235} is such a reaction possible, and then only when the U_{235} is in a much purer form than in nature, where each atom of U_{235} is associated with about 140 atoms of U_{238}. As we previously said, the harmful effect which the U_{238} has on the maintenance of the reaction is that it captures the neutrons without emitting more of them, and thus the number of neutrons decreases rather than increases. We also learned that not all of the neutrons which the U_{235}, itself, captures are successful in producing fission. Many of the nuclei reemit the neutrons in a much less energetic state than that in which they entered the nuclei, and such "weak" neutrons do not aid the chain reaction. There is a third factor which must be considered: the loss of neutrons at the surface of the reacting material. Since the neutrons are moving about in the bulk of the material haphazardly in all directions, and since, as we know, most of the volume of any mass of material is merely space, many neutrons will escape through this empty space from the reacting mass, and thus will be lost.

Therefore we see that the only process in the reacting mass which produces neutrons to maintain the chain reaction, is fission of U_{235}, but there are three processes which are using up neutrons and tending to cause their number to decrease: non-fission capture of neutrons by U_{235}, non-fission capture by U_{238}, and escape of neutrons through the surface of the reacting material. Since U_{235} is more readily fissionable than U_{238}, we may neglect the number of neutrons produced by the U_{238} fission. We must also consider non-fission capture of neutrons by other materials, which are impurities in our reacting mass. What can we do to increase the probability of obtaining the desired chain reaction by eliminating or lessening the factors which cause the losses?

To minimize the effect of impurities all we need do is get rid of the impurities. This is easier said than done, since some impurities have very noticeable effects even at concentrations as low as several parts per million, and it is difficult to produce large quantities of materials of such purity. The diluting effect of the U_{238} can be remedied only by getting rid of the U_{238}, but as we saw in the last section, the separation of the two isotopes is very difficult.

Critical Size

The escape of neutrons through the surface of the reacting mass is one effect we should be able to remedy. If we increase the size of the reacting mass, retaining the same shape, say that of a cube or sphere, we know that the volume of the material increases as the cube of any characteristic dimension, L, while the surface increases only as the square, L^2. Since the total amount of material, and the number of nuclei undergoing fission is proportional to the volume, L^3, while the number of neutrons escaping through the surface is proportional only to the surface L^2, the net effect of increasing the size of the reacting mass is to increase the possibility of maintaining the self-sustaining chain reaction, as the cube of any number greater than one increases more rapidly than its square. In other words, when we use a larger reacting mass, we cause more neutrons to be created by fission of U_{235} than are lost by escape through the surface of the material. Suppose we take a given quantity of uranium of a certain purity and a certain ratio of U_{238}: U_{235}. Now, by adding more material to the original, but retaining the same shape, let us increase the size of the material on hand. We will eventually reach a size for which the number of neutrons being produced by the fission of U_{235} is just balanced by the number lost to the U_{238}, to non-fission of U_{235}, to impurities, and by escape through the surface. For this size the number of neutrons will remain constant throught the mass. Increasing the size an infinitesimal amount more causes the number to increase rapidly. The reaction is now self-sustaining. The size at which this occurs is known as the *critical size*. A little thought will show that the critical size can be decreased (1) by decreasing the amount of impurities, i.e., using highly purified uranium, (2) by ridding the U_{235} of U_{238} by separating the two isotopes (if the isotopes are only partially separated, the greater the U_{235} content of the mixture, the smaller the critical size), and (3) by using the shape of reacting mass which has the smallest surface to volume ratio (that is, a sphere).

Even if pure U_{235} is used, there will still be a critical size for the chain reaction to occur. This is because of the long "free path" of the neutron. As was explained in an early section, the free path of a gaseous molecule is the distance it travels, on the average, before colliding with another gaseous molecule. At atmospheric temperatures and pressures the free path is about 10^{-5} cm. The free path of the neutron is the distance it must travel from one nucleus before striking another nucleus. If we consider the nuclei at stationary, by knowing (1) the target area of a nucleus, which is just its projection perpendicular to the path of the neutron, and (2) the total number of atoms in a plane, we can calculate the total area in a particular plane of atoms. The number of atoms in a plane can be calculated from the nuclear diameter and density of the material. The total area of the nuclei in the plane, divided by the total area of the plane, gives the probability of the neutron's hitting a nucleus in that plane. From a knowledge of the material's density and nuclear diameter, we can calculate the number of planes or layers of atoms per cm. in the material perpendicular to the neutron's

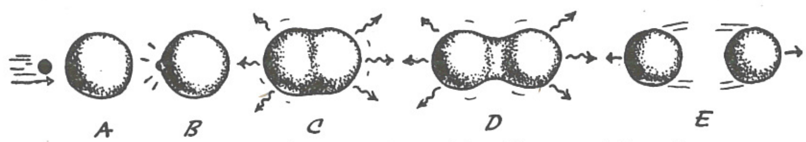

Fig. 38 Fission of Uranium Caused by Neutron Adsorption.

(a) Neutron approaches uranium nucleus, (b) Neutron captured by nucleus, (c) Excited nucleus vibrates due to energy excess, (d) Excited nucleus begins fission, (e) Two fission fragments are repelled with a large amount of kinetic energy.

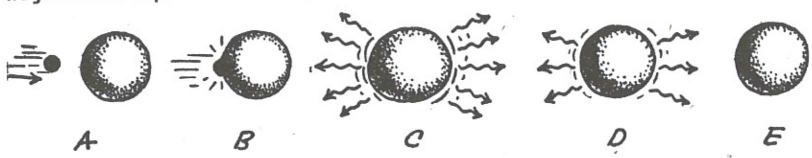

Fig. 39 Neutron Absorption by Uranium Without Fission Production.

(a) Neutron approaching uranium nucleus, (b) Neutron penetrates nucleus, (c) Nucleus in "Excited" state, emits gamma rays, and (d) dissipates excess energy, stabilizing to— (e) heavier, unexcited nucleus.

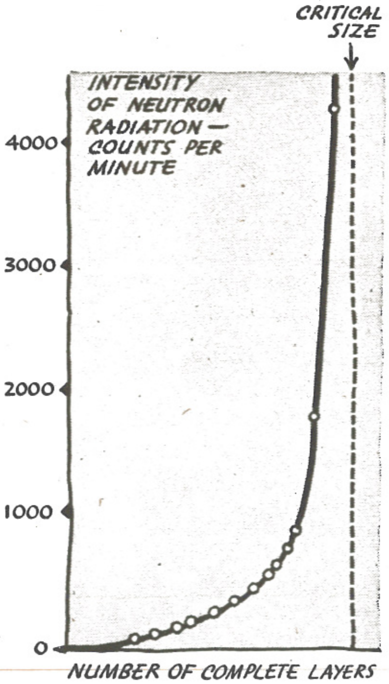

Fig. 40 Determination of Critical Size of a Uranium-Carbon Pile.

path. The reciprocal of the probability of hitting a nucleus in one plane gives the number of planes through which the neutron must go to be assured of a hit, and this number divided by the number of planes or layers per cm., gives the number of cm. through which it must travel. This is its free path through the material.

The value of the free path of the neutron is of the order of 10 cm., which means that the neutron must travel ten cm. on the average before hitting another nucleus. Thus, if the reacting mass were spherical, it would have a critical size of 10 cm. radius. The exact calculation of the free path is complicated because the neutron's collision with a nucleus causes two more neutrons to be emitted, rather than only one; however, the order of magnitude is correct. Critical sizes also exist for all chemical reactions, but because of the small free paths for chemical reactions, the critical sizes are very small, and usually do not have to be considered.

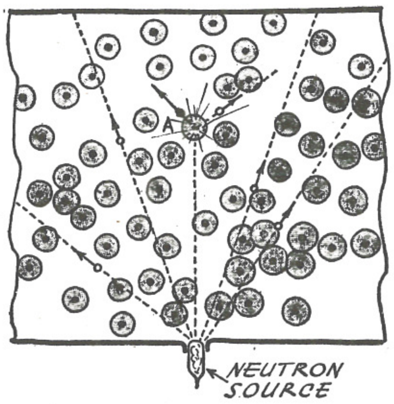

Fig. 41 Free Path of Neutrons in Matter.

The neutrons miss the nuclei on all paths shown by dashed lines, except at A. At A the neutron strikes a nucleus and is reflected downward. The struck nucleus is knocked off in a different direction.

The target area, discussed in a previous paragraph, gives a direct measure of the probability of the neutron's hitting the nucleus, if there are no other forces which need be considered. However, if the nucleus repels the neutron, or other bombarding particle, (e.g., a proton) the bombarding particle will have a smaller chance of reaching the nucleus. Thus, the repulsion has the same effect as reducing the target area, or as the nuclear physicist call it, the "cross section." Conversely, an attraction of the nucleus for the bombarding particles has the same effect as enlarging the cross section. Thus, the cross section or target area is seen to depend not only on the actual size of the nucleus being bombarded, but also upon other factors, the most important of which are the nature of the bombarding particles, and their speeds.

In the preceding paragraphs, we did not discuss the mean of reducing nonfission capture of neutrons by U_{235}. There is really little that we can do about this. The number of neutrons causing fission and the number being re-emitted are equal to the numbers having energies in excess of the activational energies for fission and re-emission, respectively. These numbers depend only on the activational energies for the two processes and on the temperature. The temperature has very little effect until we reach extremely high temperatures, which are beyond the realm of practicality, so that we may assume that the relative numbers of nuclei undergoing the two processes do not change.

Slow Neutron Reactions

We now come to a very interesting and important point. In all of our previous discussions we have been considering the fast neutrons emitted by the fissioning atoms. These fast neutrons have energies of the order of one to two Mev, and velocities of about 1/20th that of light. However, it was found by researchers of the Manhattan District that slow neutrons are also very effective in producing fission of U_{235}. The slow neutron reaction of U_{235} is a resonance process, and occurs when the neutron has an energy of about 1/40 ev. At this energy level the neutrons are moving with greatly reduced velocities. In fact their average velocity is about that of hydrogen molecules at the same temperature, and is around ten thousand times slower than that of the fast neutrons of several Mev energy content. Since the only motion and energy which these neutrons possess is that due to the thermal motion of gases according to the kinetic theory, they are often called "slow or thermal" neutrons. The effectiveness of a slow neutron depends on the fact that it has an energy corresponding to that of a certain resonance level in the uranium nucleus, and thus is able to "leak" through the potential energy barrier, even though it can not get over it, penetrate the nucleus, and cause its rupture or fission.

The discovery of the resonance capture of slow neutrons by U_{235} offers a method of increasing the possibilities of maintaining the chain reaction. When we discussed the possibility of maintaining a chain reaction by increasing the size of the reacting mass to the critical size, we saw that the critical size decreases as the ratio of the U_{235} to U_{238} increases. Actually, using a natural uranium source in which this ratio is only about 1:140, it is impossible to maintain a chain reaction, no matter how large the mass is made. If the mass is made extremely large, so that only a negligible number of neutrons are escaping through the surface, the chain reaction will still not occur, as too many neutrons that are being captured by the U_{238} and by non-fission capture of U_{235}. Now, if we slow down the neutrons so that their energy is 1/40 ev none of them will have the activational energy of several Mev needed to climb over the barrier for U_{238}. We can slow the neutrons are being captured by the the reacting mass, causing them to collide with atoms of other substances, and then return them to the reacting mass at the proper energy level—that of thermal motion. They will then bounce around the atoms of U_{235} and U_{238} until they hit a U_{235} nuclei and cause their rupture.

There is a slight drawback here, however. The U_{238} also has resonant levels at which it captures neutrons, without causing fission. An important resonance level occurs for neutrons having an energy of about 25 ev. Therefore, the neutrons will have to be kept out of the neighborhood of the U_{238} while they have energies of 25 ev, and until their energy has been reduced to 1/40th ev. The maintenance of the chain reaction by the principles we have just discussed is effected by means of the so-called "uranium pile." Briefly, the pile consists of small chunks of uranium or uranium compound, interspersed in a particular form (exact nature secret) or lattice between other chunks of a material used to slow down the neutrons. The material which slows the neutrons is known as a *moderator* since it "moderates" the neutrons' speed and reflects them back to other chunks of uranium when they can react.

Let us recapitulate a little on the operation of the pile. A source of neutrons, produced for example from a small quantity of radium and beryllium, is placed within the pile. Let us consider only one of these neutrons.

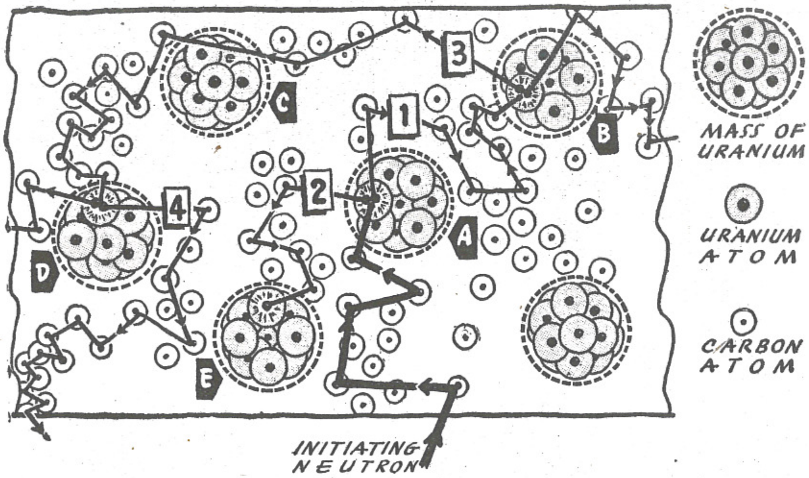

Fig. 42 Action of Uranium-Carbon Pile.

The initiating neutron from an outside source works its way through the carbon atoms, striking an uranium nucleus at A, and causing its fission. Two more neutrons are emitted by the disintegrating nucleus. The neutron following path (1) collides with carbon nuclei, these collisions reducing its speed until it is able to cause the disintegration of another uranium nucleus at B. This disintegrating nucleus gives two more neutrons. The neutron following path (3) passes through the uranium mass C without causing disintegration, and proceeds to D, where it causes further reaction. The neutron proceeding along path (2) is captured by the uranium nucleus at E, since it is moving at a relatively high speed. The neutron following path (4) escapes through the surface of the pile. The distance between collisions is proportional to the velocity of the moving neutron.

We may assume that it is able to cause the fission of one uranium nucleus since it has high enough speed to overcome the fission activation energy. The fission produces two more neutrons, elements of lower at. wt. than U, and 200 Mev of energy. This energy will be the kinetic energy of such atoms as those of krypton from the U_{235} disintegration; the two atoms produced by the fission will be moving apart with great speed, and will collide with other atoms in the pile, until all of their kinetic energy is dissipated as heat. If the volume of the moderator material is much greater than that of the little chunks of uranium, and the chunks are of smaller size than the free path of the neutron, the two neutrons will be ejected into the moderator. There they will collide with the material composing the moderator and will be slowed down by bouncing around in it until they find their way back into the uranium chunks.

Suppose only one of these neutrons causes fission of U_{235}, while the other is caught by U_{238} or some impurity and thus is lost to the U_{235}. A neutron which is caught by U_{235} but does not cause fission will be slowed down greatly, and can be further slowed down by collision with other moderator atoms. Hence it will not be lost unless it is captured by the U_{238} or escapes through the surface of the pile. With one neutron producing only one more effective neutron for fission, the pile is self-sustaining and stable. Increasing the size of the pile will minimize the number of neutrons escaping from its surface; use of very pure materials in the moderator will minimize the neutron capture by impurities, and non-fission capture by U_{235} may be neglected insofar as it causes reduction of neutrons. Thus we can regulate our conditions, so that of each two neutrons being produced by a fissioning atom, one will produce further fission in U_{235}, and the other will be captured by the U_{238}.

The first successful experiments were performed with the pile at the University of Chicago early in 1942. The pile was built of successive layers of moderator (graphite) and uranium, until the critical size was reached. It was then operated at such a rate that the energy given off by the disintegrating U_{235} atoms was at a rate equivalent to an electrical power production of one-half watt. Later, the rate was stepped up to 200 watts. A very important point must be now mentioned —the method of controlling the pile.

Once the pile reaches critical size, the number of neutrons in action at a given time will build up very rapidly according to an exponential law, and, if uncontrolled, will result in an explosion. Suppose that the pile is of such construction that each neutron formed gives on the average 1.05 more neutrons which are *effective* in producing further fission. Then after two steps there will be $(1.05)^2$ neutrons available, after one hundred steps, $(1.05)^{100}$, etc. The value of $(1.05)^{100}$ is about 100, so that after a hundred steps, there will be one hundred available neutrons, after two hundred steps,— 100x100=10,000, and after three hundred steps a milion neutrons, for each original neutron sent into the pile. The time for each step in the reaction is only about a millionth of a second, so that if no adequate controls were provided, within a time much shorter than a second, the whole pile could react and cause a violent explosion, once the critical size was reached or slightly exceeded.

The control of the reaction is very simple; it merely consists of inserting a controlled amount of "impurities" into the pile. This is done by providing channels in the pile mass through which rods of cadmium or boron steel may be inserted. These materials have a very high affinity for slow neutrons, and capture them, thus slowing down the reaction. If it is necessary to slow the reaction only slightly, the rods are pushed in only a short distance; conversely, to effect a considerable reduction the rods may be pushed in farther, or the reaction may be brought to a stand-still if desired.

Delayed Neutrons

As we just stated, the time between successive steps in the reaction is very small, and once the multiplication factor only slightly exceeds 1.000, we would expect the reaction rate to increase in such a short time that an operator would not be able to adjust the controls quickly enough to prevent the reaction's getting out of hand.

This is what would happen were it not for the fortunate phenomena occurring in the pile, and resulting in the production of "delayed neutrons." It has been found that not all of the neutrons resulting from the U_{235} fission are emitted instantaneously, that is within a few millionths of a second, but one per cent are delayed at least 0.01 second, and about 0.1 per cent are delayed as long as a minute. Thus with automatic recording and regulating instruments, there is time to regulate the controls to the desired values of neutron intensity in the pile. For example, we might operate a pile of such a size so that without insertion of control rods its multiplication factor is only 1.001. Thus every thousand neutrons produced in any given step will cause the appearance of 990 more within 0.01 second, 1000 within a minute, and 1001 in a slightly longer time than a minute. It is only the last one neutron of the thousand and one which causes the reaction rate to increase, and we can easily control this last neutron with the control rods.

Let us investigate the cause of slow neutron emission. When the U_{235} disintegrates, we know that it gives several free neutrons as well as two fragments of nearly equal size (that is, of about one-half the atomic number and atomic weight of uranium). Consider these two large nuclear fragments. The original U_{235} contained 92 protons and 143 neutrons, and its n/p ratio was about 1.6. If three of the neutrons are given off by the fission, each remaining half of the nucleus will then contain $\frac{143-3}{2}=70$ neutrons, and 92/2=46 protons, and its n/p ratio will also be about 1.6. However, an element of atomic number 46 is in the middle of the periodic table, and in the third chapter we learned that the stable n/p ratio for elements in the middle of the table is about 1.3. Thus, the fragments given off by the U_{235} fission are not stable and tend to sta-

bilize themselves to elements having permissable rations. The n/p ratio is too large; however, it may be decreased either by increasing the number of protons or decreasing the number of neutrons. Actually, the unstable fission fragments do both. They convert some of the neutrons into protons by emitting electrons or beta rays. We recall that a neutron may be considered a combination of a proton and an electron. The emission of beta rays follows the usual laws of radioactive decay, and accounts for much of the danger to personnel caused by atomic bomb residues as well as by the materials in the uranium pile. Since the activational energy for beta ray emission is less than that for emission of the large, heavy neutrons from the nucleus, beta ray emission is favored over neutron emission. However, there are still a few of the unstable fragments which have enough energy to liberate neutrons. This is not an instantaneous process, but a rather slow one, and it accounts for the production of the delayed neutrons which are so useful in controlling the pile.

Moderators

It is necessary that we consider in a little more detail the problems which the Manhattan District solved in obtaining a suitable moderator. There are two main requirements which the moderator must fulfill. First, it must slow down the neutrons sufficiently as desired, and second, it must not, itself, capture the neutrons and thus make them unavailable for production of further fission. In addition to these requirements, it must be possible to obtain the moderator material in the desired quantities, and the material must have the correct structural properties for use in the pile.

The neutrons are slowed down by collisons with atoms of the moderator, during which collisons they give up a portion of their kinetic energy to the atoms with which they collide. The most effective atoms for slowing the neutrons are those having weights closest to that of the neutron. The hydrogen atom has nearly the same weight as the neutron, and a collison between a neutron and a hydrogen atom moving only at thermal velocities results in the neutron's losing about 40% of its energy, on the average. It can be easily shown that in about thirty-five collisons, the neutron's energy will be reduced from 2 Mev to 1/40 ev. Because compounds of hydrogen will be equally effective, water and other hydrogenous materials, such as paraffin, are often used as shields against fast neutrons. However, hydrogen does not satisfy our second requirement, that it must not capture the neutrons; in fact, it very readily combines with neutrons to form heavy hydrogen, or deuterium.

$${}_1H^1 + {}_0H^1 = {}_1H^2$$

The facility with which hydrogen combines with neutrons is one of the reasons for the very harmful effect of neutrons on the human body, because the body is composed mainly of hydrogenous materials.

The lightest atom after hydrogen is heavy hydrogen or deuterium, having an atomic weight of two. It would be satisfactory as a moderator, and, in fact, some piles were operated using deuterium as a moderator. The deuterium was in the form of heavy water, and remained a liquid in the pile. This is somewhat a disadvantage to pile construction, but the heavy hydrogen could be converted into solid compounds, which might possibly be of more utility. The drawback to deuterium use is the lack of sufficient quantities of it in a pure state. Although deuterium is found in all natural sources containing hydrogen, it occurs as only 0.02% of the total hydrogen. The separation of deuterium from hydrogen presents us with the usual difficulties of isotope separation with which we were familiarized in the previous section. However, the isotope separation is easier than for those of U because of the much larger ratio of masses for the two hydrogen isotopes, 2:1, as compared to 1.009:1 for the uranium isotopes. Of the many methods which have been used for the preparation of heavy hydrogen or its compounds, the most common commercial one is the electrolysis of water. If only a portion of a given quantity of water is electrolyzed, then by a process of fractional electrolysis the proportion of deuterium in the hydrogen source may be considerably increased. This process depends on a cheap source of electric power, and for this reason the Germans erected units for production of heavy water in Norway. Dr. Niels Bohr, propounder of the Bohr theory, was forced by the Germans to work on this project before his abduction to the United States by commando units, who later destroyed the plant.

After deuterium, the lightest atoms are those of He, Li, Be, B, and C. Helium is not practical as a moderator because is it a gas and forms no compounds. Lithium and boron both capture slow neutrons, and thus cannot be used satisfactorily as moderators. Beryllium is not an abundant element, and cannot be obtained in sufficient amounts of the required purity. This leaves carbon, which, after methods had been devised for preparing it in a very pure state, was the actual material used as a moderator.

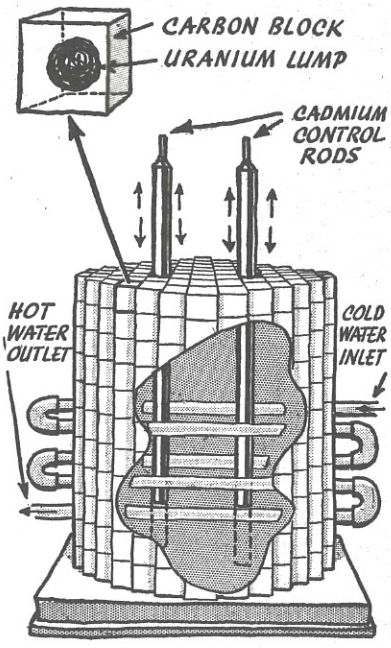

Fig. 43 Scheme of the Uranium-Carbon Pile and Controls.

Power Output From Pile

As we have learned, the pile operates by a continuous chain reaction which causes the disintegration of U_{235} to lighter, radioactive elements, and results in the production of 200 Mev of kinetic energy in the disintegration products. This energy is converted into heat, and the ability to carry away the heat of the reaction controls the speed at which the pile can be allowed to operate. For a pile operating only at a low power level, the heat may be dissipated to the surroundings by radiation, and convection, etc. However, for a large unit, or one operating at a higher power level, other, swifter means of removing the heat of reaction must be employed. This can be done by means of pipes containing circulating water or other heat transfer media. The utilization of the heat of reaction from the pile is the basis of many of the proposed industrial, peace-time uses of atomic energy, and will be discussed in a later section.

Plutonium—the Hanford Project

Throughout this section, we have talked about the non-fission capture of neutrons by U_{238}. The inquisitive reader will naturally ask, "What are the results of this reaction between the neutron and U_{238}?" It has been found that this reaction is merely a simple capture, resulting in the formation of a heavier isotope of uranium, U_{239}. This isotope is unstable, and by radioactive decay and emission of an electron is transformed into a new element-neptunium, ${}_{93}NP^{239}$. The neptunium is also unstable, and by a similar radioactive decay process it is transformed into another new element plutonium, ${}_{94}PU^{239}$. This new element, Pu, is fairly stable as far as radioactive decay is concerned, but is similar to U_{235} in its instability to neutron attack. However, since it has an atomic number different from that of uranium, it is a different element, with different chemical properties, and can be separated from U_{238} by chemical means. These chemical means are much less difficult than the isotope separation methods we have considered. We may summarize the reactions as follows:

(1) ${}_{92}U^{238} + {}_0n^1 = {}_{92}U^{239}$

(2) ${}_{92}U^{239} = {}_{93}Np^{239} + {}_{-1}e^0$, half-life of ${}_{92}U^{239}$—20 min.

(3) ${}_{93}Np^{239} = {}_{94}Pu^{239} + {}_{-1}e^0$, half-life of ${}_{93}Np^{239}$—2 days

(4) ${}_{94}Pu^{239} = {}_{92}U^{235} + {}_2He^4$, half-life of ${}_{94}Pu^{239}$—25,000 yrs.

Thus we see that the pile is continuously producing Pu as well as Np

and U_{239}. If we consider that each fissioning U_{235} atom gives two neutrons, but only one is used to maintain the chain reaction, the other one, as we previously learned, is being lost to U_{238}, to impurities, and through surface escape. If we use very pure materials, and a very large ratio of volume to surface, for practical purposes the other neutron may be considered as being lost to the U_{238} alone. Since each neutron captured by an atom of U_{238} results eventually in the production of an atom of Pu, we will have one atom of Pu formed for each atom of U_{235} reacted. Thus, a uranium source containing 0.7% U_{235} could be converted into a material containing 0.7% Pu, if all of the U_{235} were used.

The chemical and physical properties of Pu were studied, even before large quantities of it were produced, and a suitable chemical method was worked out for separating the small amounts of Pu from the U_{238} and fission products of the U_{235}. Security regulations permit very little to be said about this process. Suffice it to say that by the usual chemical means of precipitation, solution, reprecipitation, etc. the Pu can be successfully separated, and prepared in the desired state of purity. The Pu has two important chemical oxidation states (valence), IV and VI, and the chemical processes usually make use of alternations between these two states.

The successful separation of Pu from the other materials in the pile, and its ability to undergo fission in a manner similar to that of U_{235} and thus be used in place of U_{235} for the fissionable material of the atomic bomb, led to the construction of the large uranium piles near Pasco, Washington. This is the Hanford Project. The plant is located on the Columbia River, which provides a large supply of the fresh water needed for chemical processing as well as for carrying away the heat generated by the reactions in the pile. The magnitude of the heat generated may be realized, when it is considered that the cooling water, which is returned to the river after passing through the piles, causes an appreciable temperature rise throughout the whole Columbia River just below the plant site.

There are many practical difficulties, chemical, physical, biological, and engineering, which had to be solved at this plant. All operations must be carried on by remote control, with the operators protected from the radioactive materials by heavy concrete walls. The pile contains uranium in "cans" made of a material which is able to withstand the action of the radiations, the corrosive effect of cooling water, etc., but which does not capture too many neutrons itself. It is believed that cooling water runs over the surface of the cans. The reaction is not continued until all of the U_{235} is consumed. This would require too long a time to be practical. When the cans have been in the pile a sufficient length of time, they are automatically pushed out, and fresh cans of U_{235} and U_{238} replace the partially spent ones. The cans and their contents are then dissolved in acid, and the chemical separation processes started. The materials in the separation plant flow in continuous streams, all flows being remotely controlled. The plant resembles a series of small "canyons," as the open spaces between concrete walls of the different units are called.

The main danger to personnel is the presence of the radioactive fission products of the U_{235}. The water dumped back into the river must not be contaminated by these products and the fact that some of the radioactive materials are gasses necessitates that numerous steps be taken to assure that they do not foul the surrounding atmosphere. Very rigid precautions were taken at this plant, as well as at the Clinton plant and in other units and laboratories where radioactive materials were handled. The biological effects of these radioactive materials will be discussed in section XI.

X: The Atom Bomb and Hiroshima

EXPLOSION: THEORY AND PRACTICE

IN THE previous sections we have discussed atomic and nuclear theory in some detail so that the reader may be able to understand the development of the atomic bomb, and the difficulties which beset its developers. In these sections we have been fortunate in being able to present a large quantity of factual material. We now come to the section which will be climactic to most readers, and it is unfortunate that in this section we will be able to present very few facts, but only basic theory and conjecture as to the theory's application.

We have learned that a mass of U_{235}, plutonium, or enriched U_{235} of size equal to or greater than critical, will detonate violently when exposed to a source of neutrons. However, no detonation can be effected in a mass of sub-critical size. The problem then resolves itself into the production of the U_{235} or Pu in sufficient quantities of sufficient purity, and the bringing together of sub-critical masses of the explosive material in a satisfactory manner to form a critical or above critical mass, which will undergo the chain reaction and detonate.

We have already discussed the methods of producing the active material. This work was carried on by the Clinton and Hanford plants, by the Metallurgical Laboratory, and by many other scientific institutions throughout the country. The second part of the problem, that of assembling the active material to form a bomb, was mainly investigated by the Los Alamos Project, located in the arid regions of northern New Mexico, and headed by Dr. J. R. Oppenheimer. In this forbidding desert on July 16, 1945 occurred the first man-made atomic explosion. The culmination of the concentrated effort of thousands of scientists, engineers, and workers, this explosion heralded the new age of atomic power.

Before launching a discussion of the construction and operation of the atomic bomb, it will be useful for us to study first some of the basic concepts of explosions in general. An explosion is defined as the sudden generation and liberation of energy, occurring before the constituents which cause the reaction and the reaction products have had time to separate appreciably.

The most important factor in determining whether or not an explosion occurs in a reacting mass is the speed of the reaction. If the energy of the reaction can be transferred to the surroundings as rapidly as it is evolved, there is no explosion. On the other hand, an explosion is said to occur when the reaction products and energy cannot be dissipated as quickly as they are formed. There is no difference in the basic processes involved, only in the reaction rates. Thus a boiler producing steam does not normally cause an explosion, since the energy of the expanding steam is transferred to the machines which the steam operates. However, an explosion results when the steam cannot expand but is confined in the boiler. The pressure builds up until the walls of the boiler rupture. The sudden expansion of the gas (energy liberation) cannot be immediately absorbed by the boiler's surroundings, and we say that an explosion has occurred. The same concepts hold for chemical reactions. Thus the burning of coal in air proceeds at a slow enough rate for the heat of the reaction to be dissipated. However, if the coal is finely ground, heated, and thrown into a container of oxygen, the reaction proceeds so quickly that an explosion occurs.

The so-called "high explosives" are usually chemical compounds in the metastable state, such as TNT or nitroglycerin. By the addition of a small amount of activation energy, as from a spark or shock, a reaction is initiated which generates quantities of gases in a time of approximately a micro second. In this short time, the reaction products cannot separate or expand as in normal reactions, and an explosion results. Pressures of the order of 10^7 lbs. per sq. in. occur during such explosions. From what we have previously learned—that one pound of fissioning uranium produces energy equivalent to twenty million pounds of TNT—we should expect a

much higher pressure to be produced by the atom bomb than by TNT. Presently we shall discuss the pressures encountered in the explosion of an atom bomb.

Having obtained a clear idea of what we mean by an explosion, let us examine the relations between the various factors influencing an explosion. Our discussion will be only approximate, but it will give the general idea of the magnitudes of the factors considered. Let us assume a cube of explosive material such as TNT or uranium. Let the edge of the cube be L cm. and its density D. For simplicity we will suppose that the effect of the explosion is to fracture the cube into two equal fragments at a plane parallel to one of the faces of the cube. Suppose that the pressure generated and acting on these two newly formed faces has a uniform value P, and is generated in a time, t. The force on each inner face is the pressure times the area of the face.

$$F = PL^2. \qquad (1)$$

This force tends to drive the two faces apart, with an acceleration which we can easily calculate. Let the velocity of separation of the two halves equal $2v$, and the total mass m. Then the total momentum is mv, and the force, which equals the rate of change of momentum, is

$$F = \frac{mv}{2t}. \qquad (2)$$

The total mass, m, is DL^3. Substituting this value of m in equation (2), and equating the two expressions for the force in equations (1) and (2), we obtain

$$2Pt = DLv. \qquad (3)$$

If we assume further that during the time t the material expands to only twice its original volume, then the distance of expansion is L, and the velocity of expansion of each half of the original cube is v

$$v = \frac{L}{t}. \qquad (4)$$

Substituting this value of v into equation (3), and solving for t, we may obtain a final expression

$$t = \frac{LD}{2P}. \qquad (5)$$

Although this equation is based upon many assumptions which are rather approximate, it gives a very simple relation between the various factors, t, D, L, and P. Of particular importance is the relation between t and P. Notice that if D and L are held constant, t must decrease as P increases.

If we substitute approximate values into the equation, using TNT, let L equal one cm., $D = 1$ gm/cc., and $P = 10^{12}$ dynes per cm^2 (10^7 lbs/sq. in.). This will give a value of t approximately equal to 10^{-6} seconds or one micro second. Now using the same values of L and D, but remembering that the pressures developed by the atom bomb are roughly a million times greater than those by TNT, we can see that the time, t, will now be $\frac{1}{10^3} = 10^{-3}$ times as great for the atomic bomb explosion. Hence, the atomic bomb reaction must take place in $10^{-3} \times 10^{-6} = 10^{-9}$ seconds to cause the desired explosion. Is it possible for the reaction to go completely in such a short time?

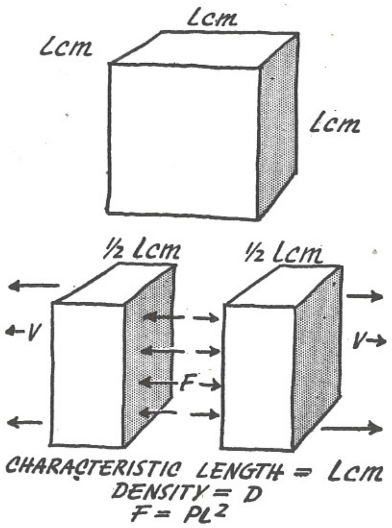

Fig. 44 Elementary Explosion Concepts.

We have previously said that the mean free path of a neutron in the uranium mass is about ten cm. If the neutron's energy is one Mev, by substitution into the kinetic energy equation, $K.E. = \frac{mv^2}{2}$, we find that the neutron's velocity is about 10^9 cm. per second. Thus the time for the neutron to travel between two successive disintegrating nuclei is $\frac{10}{10^9}$ or 10^{-8} sec. But this is the time for only one step. For all the nuclei in one gram of uranium to be disintegrated, assuming for the moment that the chain reaction can be made to go in this small amount of material, we may calculate the number of steps needed. There are $6.03 \times 10^{23} \div 235 = 2.5 \times 10^{21}$ nuclei in a gram of uranium. Assuming that each step in the chain produces two neutrons, n steps will produce 2^n neutrons. Equating

$$2^n = 2.5 \times 10^{21} \qquad (6)$$

we can solve and find that n is about 71 steps. Since the actual bomb is larger than one gram, more steps will be required. We may use 100 steps as an approximation. Thus the total reaction time will be about 100×10^{-8} or 10^{-6} seconds. Therefore the reaction time for the atomic bomb is about the same as for a TNT bomb.

This reaction time of 10^{-6} is undesirable, as we just found that it should be only one-thousandth as great to assure complete reaction of the uranium. The difficulty lies in the fact that the reaction of the first fraction of the material drives the mass apart, so that a mass which was of critical size before the reaction began, soon consists of many sub-critical masses and the reaction rapidly comes to a halt.

There are two things which can be done to alleviate this situation. One is the use of larger than critical masses of material. However, this change will not greatly aid the reaction, as the number of critical masses must be held to practical limits of handling. The other improvement is to surround the active uranium mass by a heavy, inert, material, which will keep the fragments of the reacting material together for a short while. This material, called the "tamper," is made of a heavy metal, such as lead. It has been found that the value of the tamper is practically independent of its mechanical strength, the most important property being its density. Materials of greatest density are most desirable for use as tampers. The tamper also serves another purpose. This is the reflection of stray neutrons, which might otherwise escape from the surface of the reacting mass. Again, a dense material is desirable since it contains more nuclei per unit area, and has a better chance of reflecting the neutrons. This is analagous to the reflection of a golf ball from a thick forest onto the fairway of the course. The denser the forest, the more probability there is that the ball will strike a tree and be reflected. Obviously the tamper must be made of a material which does not itself capture neutrons by any of the nuclear transmutation processes we have discussed.

Depite the utilization of more than one critical mass for the bomb, supplemented by a tamper, it is well known that the bomb is rather inefficient. Hence, these measures are not too effective. It has been stated that the energy liberated by an atomic bomb is equivalent to that of 20,000 tons of TNT. The energy liberated per pound of exploding TNT is approximately 5,000 btu per pound. Thus, the energy liberated by 20,000 tons of TNT may be calculated. This value is about the same as that theoretically obtainable by fission of only five pounds of U_{235}.

However, it is well known that the amount of material in the bomb is considerably greater than five pounds, probably several hundred pounds. Therefore, it can be deduced that the bomb's efficiency is rather low, probably only a few per cent. Further research will, no doubt, be directed toward methods of increasing the bomb's efficiency. It has been stated that the bomb dropped on Nagasaki was considerably more efficient or at least more effective than that dropped on Hiroshima.

Assembly and Detonation Of the Bomb

The methods used to assemble and detonate the bomb are top military secrets, and only the roughest of conjectures may be presented here. If a mass of uranium of greater than crit-

ical size were made, it would detonate spontaneously, the reaction being instigated by stray neutrons, which are always in the atmosphere as a result of cosmic ray activity. Hence, we must start with two or more pieces of subcritical size, and bring these pieces together at the proper time in a short interval. This time interval must be small enough to insure that the parts of the bomb will not be blown apart by the reaction they initiate before the reaction has been able to proceed to some extent. Because of the rapid reaction time (a micro second or less) we assume that the two parts must be brought together during a time interval no longer than a micro second.

Let us assume that we have two pieces of less than critical size, their combined mass and shape being more than critical size. If these pieces are separated by an air gap of say one cm., there will be a sufficient number of neutrons escaping to prevent the chain reaction's ensuing. If the distance separating the two halves of the bomb is one centimeter, and they must be brought together in a micro second or less, then the velocity of their approach must be no less than $1/10^{-6}$ or 10^6 cm. per second. This is a thousand meters per second, and is the same order of magnitude as the velocities of projectiles shot from military guns. This suggests that a projectile such as a slug of U_{235} be shot between the two halves forming a "weld" which will give, in effect, a solid mass of uranium above the critical size. Thus the chain reaction will be possible.

Another method is shown schematically in figure 45. However, it must be remembered that these methods are pure conjecture. We can only present enough material on the subject of the bomb construction and assembly, tampers, and critical mass to indicate the problems which must be solved, and the general principles involved.

Effects of an Atomic Bomb Explosion

So much has been published in the newspapers and popular magazines about the bombing of Hiroshima and Nagasaki that we need not go into any great detail to impress upon the reader the destructive power of the atom bomb. However, it is important to remember that the bomb's main virtue lies in its ability to saturate the enemy's defenses so that he is totally unable to defend himself and fight back the attack on his cities. Quoting an official report before the Senate Atomic Energy Committee, "of 300 registered physicians in Hiroshima, 260 were either killed or disabled so as to be unable to aid the injured. Of 2400 nurses, orderlies, and trained first-aid workers, 1800 were made casualties in a single stroke. Of 33 modern fire stations in the city, 26 were useless after the blast, and three-quarters of the firemen were killed or missing. Not one hospital in Hiroshima was left in condition to shelter patients from the elements alone. Power and telephone service were out throughout the city. Debris filled the

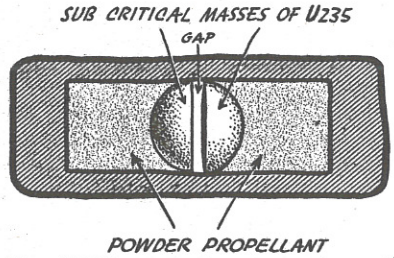

Fig. 45 Schematic Representations of Bomb Assembly.

streets and hundreds of fires raged unchecked among the injured and dead."

These are not the words of a sensational tabloid sheet, but those of a prominent scientist, one of a group appointed by the U. S. Government to evaluate the effects of the blast. The wide extent of the damage will be more easily understood after considering the source of the explosion's energy. In the words of one of the same group of scientists, "When the bomb is detonated in the middle of a city it is as though a small piece of the sun had been instantly created. There is formed what we have called a ball of fire, which is a hot glowing mass something about a third of a mile across, with a temperature in its center which may be as high as 100 million degrees Fahrenheit." The effects of the formation of this small piece of sun are as one would expect—a terriffic shock wave of displaced air—winds having a velocity of 500 to 1,000 miles per hour. Simultaneous with the explosion great quantities of radiations are emitted. These rays, more intense than X-rays, burned everyone within the blast area exposed to them.

The blast effect destroyed one-story buildings in an area of a mile and a half radius from the point at which the bomb was dropped. Brick multi-story buildings were destroyed rather generally up to 5,700 feet from the center of the explosion. Reinforced concrete buildings up to 2,000 feet away had one-third their area rendered useless. These figures for the Hiroshima bombing give the damage caused by the blast alone, and do not include the damage caused by the fires of secondary origin. Widespread fires resulted from broken gas mains, overturned stoves, etc.

A large percentage of persons who survived the blast and fires later succumbed to the internal burns caused by the radium-like emissions from the bomb. The fission product of U_{235} are mainly radioactive, liberating alpha, beta, and gamma rays, as well as neutrons. The radiations affect the blood-forming tissue in the bone marrow, and the whole function of the blood is impaired. The blood ceases to coagulate, oozes in many spots through the unbroken skin, and seeps internally into the cavities of the body. The white blood cells, fighters against infection, do not reproduce normally. Thus, infection prospers, and the victim dies, usually within two or three weeks after exposure.

One is naturally interested in methods of protection, if any, against the explosion. Scientists generally concede that from five to ten feet of concrete or its equivalent are necessary for protection from the blast itself, while extra heavy sub-surface shelters are required for reasonable protection against the radiations. Some engineers and architects believe that the best protection is an underground shelter with a roof of several feet of reinforced concrete. However, since the radiations from the bomb products persist for a considerable period after the explosion, it would be necessary for personnel to remain underground for several days after the blast. Obviously the construction of such shelters for the entire population of a large city would be quite a problem, not to mention the difficulty of providing that the entire population be in the shelters at the time the bomb was dropped. It would appear that a more practical solution would be the assurance that a bomb never be dropped. Such international control measures are, however, beyond the scope of the present dissertation. The reader is advised to devote some attention to the publication "One World or None," written by the Federation of American Scientists, and published by the McGraw-Hill Book Company. This pamphlet contains a wealth of material both on the effects of atomic energy, and its control, the most pressing problem of our times.

PERIODIC ARRANGEMENT OF THE ELEMENTS

Series	Period	ZERO GROUP	GROUP I R_2O	GROUP II RO	GROUP III R_2O_3	GROUP IV RH_4 RO_2	GROUP V RH_3 R_2O_5	GROUP VI RH_2 RO_3	GROUP VII RH R_2O_7	GROUP VIII		
0												
1			HYDROGEN H =1.0078 No. 1									
2	1	HELIUM He. =4.002 No. 2	LITHIUM Li =6.940 No. 3	BERYLLIUM Be. =9.02 No. 4	BORON B =10.82 No. 5	CARBON C =12.00 No. 6	NITROGEN N =14.008 No. 7	OXYGEN O =16.000 No. 8	FLUORINE F =19.00 No. 9			
3	2	NEON Ne. =20.183 No. 10	SODIUM Na =22.997 No. 11	MAGNESIUM Mg. =24.32 No. 12	ALUMINUM Al =26.97 No. 13	SILICON Si =28.06 No. 14	PHOSPHORUS P =31.02 No. 15	SULFUR S =32.06 No. 16	CHLORINE Cl =35.457 No. 17			
4	3	ARGON A. =39.944 No. 18	POTASSIUM K. =39.10 No. 19	CALCIUM Ca. =40.08 No. 20	SCANDIUM Sc. =45.10 No. 21	TITANIUM Ti =47.90 No. 22	VANADIUM V =50.95 No. 23	CHROMIUM Cr =52.01 No. 24	MANGANESE Mn =54.93 No. 25	IRON Fe =55.84 No. 26	COBALT Co =58.94 No. 27	NICKEL Ni =58.69 No. 28
5			COPPER Cu. =63.57 No. 29	ZINC Zn. =65.38 No. 30	GALLIUM Ga =69.72 No. 31	GERMANIUM Ge. =7260 No. 32	ARSENIC As =74.93 No. 33	SELENIUM Se =79.2 No. 34	BROMINE Br =79.916 No. 35			
6	4	KRYPTON Kr. =82.9 No. 36	RUBIDIUM Rb. =85.44 No. 37	STRONTIUM Sr. =87.63 No. 38	YTTRIUM Y =88.92 No. 39	ZIRCONIUM Zr. =91.22 No. 40	COLUMBIUM Cb =93.3 No. 41	MOLYBDENUM Mo. =96.0 No. 42	MASURIUM Ma =? No. 43	RUTHENIUM Ru =101.7 No. 44	RHODIUM Rh =102.91 No. 45	PALLADIUM Pd =106.7 No. 46
7			SILVER Ag. =107.880 No. 47	CADMIUM Cd. =112.41 No. 48	INDIUM In =114.8 No. 49	TIN Sn. =118.70 No. 50	ANTIMONY Sb =121.76 No. 51	TELLURIUM Te =127.5 No. 52	IODINE I =126.932 No. 53			
8	5	XENON Xe. =130.2 No. 54	CAESIUM Cs =132.81 No. 55	BARIUM Ba. =137.36 No. 56	LANTHANUM La =138.90 No. 57	CERIUM Ce =140.13 No. 58						
9												
10	6					HAFNIUM Hf =178.6 No. 72	TANTALUM Ta. =181.4 No. 73	TUNGSTEN W =184.0 No. 74	RHENIUM Re. =186.31 No. 75	OSMIUM Os. =190.8 No. 76	IRIDIUM Ir. =193.1 No. 77	PLATINUM Pt. =195.23 No. 78
11			GOLD Au =197.2 No. 79	MERCURY Hg =200.61 No. 80	THALLIUM Tl =204.39 No. 81	LEAD Pb =207.22 No. 82	BISMUTH Bi. =209.00 No. 83	POLONIUM Po. =209.99 No. 84	ALABAMINE Am. =? No. 85			
12	7	RADON Rn =222 No. 86	VIRGINIUM Va =? No. 87	RADIUM Ra =225.97 No. 88	ACTINIUM Ac =227.02 No. 89	THORIUM Th =232.12 No. 90	PROTOAC- TINIUM Pa. =231.03 No. 91	URANIUM U =238.14 No. 92	No. 93			

ELEMENTS NOT CLASSIFIED IN THE TABLE ABOVE

PRASEODYMIUM Pr. =140.92 No. 59
NEODYMIUM Nd. =144.27 No. 60
ILLINIUM Il. =146.(?) No. 61
SAMARIUM Sm. =150.43 No. 62
EUROPIUM Eu. =152.0 No. 63
GADOLINIUM Gd. =157.3 No. 64
TERBIUM Tb. =195.2 No. 65
DYSPROSIUM Dy. =162.46 No. 66
HOLMIUM Ho. =163.5 No. 67
ERBIUM Er. =167.64 No. 68
THULIUM Tm. =169.4 No. 69
YTTERBIUM Yb. =173.5 No. 70
LUTECIUM Lu. =175.0 No. 71

NEW ELEMENTS

NOTE: The following elements have been discovered in conjunction with the work of the Manhattan District.

NEPTUNIUM, Np, At. No. 93, At. Wt. 239
PLUTONIUM, Pu, At. No. 94, At. Wt. 239
AMERICIUM, Am, At. No. 95
CURIUM, Cm, At. No. 96

EFFECTS OF THE BOMB BURST

An atomic explosion, regardless of its location will result in four types of blast effects, namely: (1) thermal blast; (2) air blast; (3) solid blast; (4) radiation blast. The first three will vary only quantitatively from similar blast effects of other forms of explosion, all quite familiar and frequently encountered in pre-atomic warfare. The radiation effect, however, is something which is new, X-radiation being the nearest prototype with which we are at all familiar. This offers but a poor conception of the problems which arise in "total body radiation" with neutrons, beta and gamma rays and alpha particles or from the ingestion or aspiration of radioactive particulates and the resultant biological changes.

In the event of an air explosion, the radio-active cloud rises quickly to a height of sixty or seventy thousand feet and is diluted and disseminated over a very considerable area so that the residual effects in and about the area of the explosion are of relatively little importance. In the under water type of explosion, however, the radioactive cloud is almost entirely confined within the rising column of water and is, shortly thereafter, deposited in the immediate vicinity of the blast together with the radioactivity which has been induced in the water and the marine life. It can readily been seen that the latter condition imposes a hazard of almost unbelieveable proportions from radio-activity alone and to this must be added the fact that the unfissioned material of the bomb as well as many of the fission products have extremely toxic properties.

It will be necessary, therefore, for the medical officer to have information not only of the biological effects which are produced and the possibilities of treatment, but also the methods of detection of the hazard, means of protection and avoidance, safety allowances of exposure, and of his role and responsibility in the varied aspects of the problem.

Hazard of Explosion

In order to convey adequately and briefly a working understanding of the radiologic hazards of atomic explosion and the peculiar patterns these hazards present, a rather crude series of diagrams has been prepared to picture graphically for the beginner the many different forms in which the hazard may appear.

In the first place, it is desirable to point out that there are two main types of hazard and that these two differ markedly in their basic characteristics, each requiring an entirely different approach. This may be confusing unless clearly differentiated in the mind of the individual.

The first type of hazard is that of external body radiation. This is in all respects similar to that which would be encountered if the individual were exposed to a giant x-ray machine except that the rays would, in the first instance, be coming from all directions instead of from a single source. This form of hazard is well known in medicine and in certain of the industries. Certainly, the atomic bomb has provided no new information as to the qualitative characteristics of this type of radiation. On the other hand, never before has this type of radiation been encountered when it consisted of such a variety of forms, with such a wide range of energies, nor when covering such a wide range

of effectiveness. It is impractical, therefore, for one to think of this form of external radiation as directly comparable to the hazards of an x-ray machine altho the concepts of protection which have been developed and applied to x-rays are applicable to certain aspects of the hazards of atomic explosion. The essential difference is, as has been said before, that the x-rays come from a point source (diagram 1) whereas the ionizing radiation resulting from atomic explosion comes from an "extended" source (diagram 2).

To describe this difference in the pattern of the hazard, the radiologist speaks of this as the "geometry" of the radiation and it is of great importance in the understanding of the characteristics of radiation dangers. The maximum permissable exposure limit of 0.1 roentgen per 24 hour day is based upon "total body radiation". If exposure was from a point source and the area of exposure greatly reduced, as to a few square centimeters, several thousand roentgens may be administered without danger of general injury to the patient. This is not infrequently done in the case of small lesions in children. This is an unusual instance, however, and does not permit us to relax our respect for the tolerance limits which have been established for purposes of safety. When an individual receives total body radiation of 400 roentgens, even over a period of time, it is almost certain that that individual will die. Three hundred roentgens is likely to be a fatal dose. Between one and three hundred, serious injury is almost certain to occur. Between twenty-five and one hundred, there will be some injury, probably not enough to seriously cripple or endanger the future health of the individual. On the other hand, we do not know at the present time what effect these smaller doses may have on gonadal tissue or what far reaching genetic changes may be produced. Below twenty-five roentgens, it is unlikely that any injury of importance will occur altho many well informed radiologists feel that doses as small as ten roentgens may have some subtle injurious effect.

Certain factors have an important bearing on the nature and extent of the injury sustained. They are primarily characteristics of the radiation rather than of the individual and include:

(1) The "size of dose delivered" which is usually expressed in total roentgens of exposure. Roughly, the greater the amount of irradiation, the greater the absorption by the tissue and the greater the resultant injury.

(2) The "Hardness" of the ray has a bearing on the ability of the ray to penetrate. In general, the shorter the wave length of the ray the more penetrating it is and the greater is the possibility of absorption and resultant injury.

(3) The "duration of exposure" is of great importance altho it is now thought that a large dose given, or received, in a very short time may not be as fully absorbed as a smaller amount received over a longer period of time.

(4) The size of the area irradiated. The larger the area exposed to irradiation, the greater the absorption.

(5) In general, gamma rays and neutrons are more penetrating and damaging than beta rays.

(6) The greater the energy of the radiating medium, the greater the resultant damage.

In chemical warfare, CT is a symbol used to indicate the toxicity of a compound. It is not directly applicable to radiology but does make a convenient aid in evaluating grossly the seriousness of a hazard. In the expression, C represents the concentration of the poisonous agent and T the time or duration of exposure to the agent. This is demonstrated in diagram 3. The effective dose is represented by the square area of rectangle and, in general, when a lethal dose or an injurious dose is mentioned, it refers to this combination of time and concentration and is expressed in terms of total dosage.

Thus, for a lethal dose, the concentration of a gas must be five times greater if exposure time is five minutes than would be required if exposure time were twenty-five minutes.

A very comparable situation exists in total body radiation. There is a great deal of evidence to show that the "total amount of radiation received" is the factor which decides the severity of the resultant damage and that the time factor, that is, the period of time over which this dosage was absorbed, is of lesser importance. This is, of course, not mathematically true in extreme cases where very minute doses might be absorbed over a period of years and no damage occur altho the total dose be considerable, but for purposes of radiological safety, it must be considered as a true and reliable working principle.

Internal Radiation

This second type of hazard is quite different from external radiation. It is a type of hazard which is encountered in the radium industry, particularly in the radium dial painter's laboratory. It is an internal poison comparable in many ways to any chemical type of internal poison, particularly by the heavy metals. It has long been known that Radium, ingested or inhaled, even in dilute form and regardless of its chemical composition, tends to enter the blood stream and deposit in the bones. In some of the bones, very little harm may result but when it settles in the blood forming marrow, the characteristic picture of Radium poisoning results. An exactly similar picture may result from the ingestion or inhalation of particulates of the fissionable material or the fission products of the atomic bomb.

The alpha particles which are emitted by these materials are extremely high energy particles and, altho they have a very limited range and low powers of penetration, they are capable of producing some of the most insidious and destructive of the radiation injuries. It is important to re-emphasize that, from a standpoint of external radiation, the alpha particle has an almost negligible effect. It is only when the alpha emitting materials are absorbed by the body that destructive effect becomes important.

This has added significance when it is remembered that alpha particles are very difficult to detect and their presence easily overlooked or disregarded by the uninformed. There is no instrument suitable for field use which will detect alpha particles. Instruments for the detection of gamma and beta presence will be later described. It may be pointed out here, however, that under field conditions, it is necessary to calculate the amount of alpha hazard present from the measurements of beta and gamma radiations. An understanding of this may be obtained by referring to diagram 4 which is a characteristic decay curve. It will be noted that the intensity of radiation falls off with time. By using certain information supplied by radio-chemical analyses, determining the intensity of beta and gamma radiation at any given time, and referring back to the curve, it is possible to estimate the alpha intensity at that particular time and place. This is a time consuming and laborious method requiring special techniques and it is also true that there maybe some discrepancies in the curve as shown in diagram 5. Further, due to natural weathering and the transferrence of contaminated material from one place to another, it is possible for the curves to be given an acceleration in their downward course. The material which is likely to be the most resistant over a period of years consists of the long life fission products which are alpha emitters. One can readily understand, therefore, the need for particular care.

Protection against this hazard is accomplished by avoidance only. Inhalation can be avoided by the employment of suitable oxygen rescue breathing apparatus or gas masks with appropriate filters. Access through the skin can be prevented by wearing clothing which prevents contact of the particulates with the skin, by measures of hygiene, and the care of possibly contaminated wounds. One of the most important principles, is the development of a proper understanding of what the hazard is, its peculiarities and characteristics. Only on such a foundation can an approach be made to the solution of the safety problems which this form of hazard presents.

At the time of atomic explosion, there is emitted an intense radiation which includes beta and gamma rays and neutrons together with radiant heat and light. Effective ranges of these factors differ but in each, the intensity decreases with the distance from the source. The range to which neutrons are emitted is less than the range of gamma rays. The infra red and ultra violet rays, in intensities sufficient to injure skin at least temporarily, extend to a distance somewhat beyond that of the gamma rays. The direct radiation which occurs at the time of explosion is shown graphically in diagram 6 which indicates the type of radiation to which an individual in the open would be exposed to if within the range of the gamma rays. In this type of exposure, only the side of the individual exposed to the direct rays would be effected. Flash burns and eventual loss of hair in those individuals who survive would be unilateral. Practically, this purity of exposure is almost impossible since there would always be some reflection of rays from the ground and from nearby objects. This reflecting effect is known as "scattering" and is most characteristically seen inside a building. (See diagram 7). The gamma rays entering the building would be scattered in such a way that the total body radiation would be considerable and important as a killing agent. It would be possible for an individual so exposed to accumulate a lethal exposure as a result of over all radiation without having sufficient local exposure to produce loss of hair. An individual in this position would of course, be almost completely protected from the infra red and ultra violet rays.

At the time of explosion, a "ball of fire" is formed, represented by the central circle in diagram 8. This ball of fire continues to emit radiations for a matter of several seconds during which time it is rising from the original point of detonation. In a relatively short time, it reaches a height from which none of the radiations reach the earth. Therefore, there is a moving source of radiation which, as it goes skyward, subjects the individual on the ground to continuous exposure during the time that it is in range of the individual. The total effect will be, then, a combination of the initial "instantaneous" radiation of extremely short duration, and the "delayed" radiation which lasts for several seconds.

Induced Radioactivity

As a result of neutron bombardment, certain elements become artificially radioactive and, following the atomic explosion, constitute what is termed "induced activity". One form of induced activity is illustrated in diagram 9. In sea water there are several elements including sodium, chlorine, and iodine, which may become radioactive in this manner. Of these, by far the most important is sodium. It emits both beta and gamma rays. It has a relatively short half life, however, so that in a few days there is little hazard from an external radiation standpoint. Certain metals, particularly those containing copper, bronze, or manganese may be made radioactive. Also certain soils, drugs (notable Salvarsan), table salt, and even on occasion the gold fillings of teeth may become artificially radioactive and constitute a hazard.

The induction of radio-activity in the soil is of particular interest and importance because it is possible, by the use of instruments presently in use, to detect and measure this activity from the air at a height of over a thousand feet and thus chart a geometrical outline of the areas of contamination together with the intensity. This is of particular importance over land areas but is also important in marine survey where activity has been induced in the sea water and in both plant and animal marine life.

Fall Out

More important than the induced radio-activity, however, is the contamination which occurs due to the "fall-out" of radio-active materials from the atomic cloud. This, as has been previously noted, is of almost unbelievable seriousness in the case of an underwater blast. The pattern of fall-out will vary considerable with wind and weather conditions as well as with the location of the detonation. Humidity, rain, and wind will affect the height

to which the atomic cloud will rise as well as the rapidity and location of the radio-active deposit. In the case of under or over water explosion, tides and currents will affect the speed with which the contaminents will be disseminated.

Fall-out contamination of a surface ship is illustrated in diagram 11. Contamination of this type presents a combination of internal and external hazard to personnel and consists of unfissioned particles of the metal of the bomb as well as fission products. Early, following contamination, external body radiation will be of most serious importance as most of the fission products have relatively short half lives but those which have long half lives will continue to be important internal radiation hazards long after the beta and gamma emitters have decayed to a negligible level.

Figure 12 illus trates the contamination of a ship's hull as the result of sailing in contaminated waters. This type of contamination will first be noted on the under-water body surface of the ship particularly around the green sea growth at the water margin. Crustaceans and algae have been found to have the faculty of concentrating the activity from the water and barnacles become particularly "hot". It will soon be found, also, that salt water lines and, particularly, condenser lines, will be radio-active, the scale in the lines apparently concentrating the activity much the same as the marine growth does.

Figure 13 indicates the contamination of the sea floor. In shallow areas or in diving operations, this may become an important factor. The activity will be largely confined to sea growth in most cases since the tides and currents will disseminate the actual water contamination both direct and induced.

Figures 14 and 15 indicate land contamination at a distance from the original explosion and demonstrate the importance of aerography and terrain in the distribution of the fall-out. Figure 14 gives a graphic description of what occurred in New Mexico fifty miles northeast of the point of detonation. The particulate matter was in the form of vaporized sand to which the fission products adhered. This material fell-out onto a herd of Herford cattle which later developed white, spotty dappling of their red coats due to the local effects of the particulate radio-activity on the individual hair follicles. Figure 15 represents the deposit of the fall-out at Nagasaki. Note that the cloud passed over two hills and several miles distance before depositing in a small area of the second hill not far from the reservoir.

Contamination

An additional type of contamination has not so far been mention but is of utmost importance. Actually, it consists of re-contamination and is the result of the carrying in of radio-active materials to otherwise "clean" areas. Personnel who have been directly contaminated and those who have had access to contaminated areas are likely to carry this contamination on their feet, hands, or clothing, or on articles of any kind which they have attempted to salvage from the contaminated area. This is to be avoided if at all possible and necessitates the wearing of protective* clothing by rescue parties, the removal of "hot" clothing and, if necessary, repeated bathing before coming from a contaminated to a clean area. Extreme vigilance and careful and constant monitoring is essential.

Industrial Problem

The above type of contamination is encountered under conditions other than actual atomic explosion and is important to the medical officer in his role as an industrial

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*Note: The word "protective" is not meant to imply protection against radioactivity but only protection of the individual against contamination with radioactive materials.

Hygienist. If atomic power plants come into use by the service or if atomic power is in the future used in ships of any variety, this will become increasingly important. Prevention of undue exposure of personnel to the toxic or radio-active effects of fissioning material or fission products will be the province of the medical department. This will necessitate a general knowledge of the implications of radiological safety on the part of all hands plus very specialized and detailed knowledge of certain phases by a few.

EFFECTIVE RANGES: AND THE ESTIMATION OF PROBABLE CASUALTY PRODUCTION AT THE TIME OF AN ATOMIC BOMB EXPLOSION

For purposes of planning, the approximate ranges within which injuries to personnel could be anticipated for the various types of hazard, are given.

When the bomb is detonated in the air as at Nagasaki and Hiroshima, or on the surface of the ground, injuries may be expected within these ranges:

Blast (direct, unshielded)	1,300 - 1,500 yards
Blast (indirect effects)	3,000 yards
Radiations (instantaneous):	
Infra-red	3,000 yards
Ultra-violet	2,500 yards
Visible light	10,000 yards
Ionizing radiation	2,000 yards
Neutrons	700 yards
Fission products	Wide distribution in air
Non fissioned material	Wide distribution in air

For planning purposes, many casualties would be anticipated among personnel exposed in the open within 3,000 yards of an air burst bomb. While ordinary buildings would provide some protection against flash burns, they would provide relatively little protection against ionizing radiations and might increase the chances of indirect blast and fire casualties due to falling and burning of buildings. An estimate of the number of casualties in an air burst would be 1/3 immediate deaths, 1/3 early deaths and 1/3 serious casualties requiring much medical attention. This would include all personnel within the 3,000 yards range.

Whereas personnel in ships would receive some benefit from shielding from gamma rays, this number would probably be offset by an equal number being injured by effects other than those calculated here. This would not include casualties which might arise subsequently from personnel being exposed to residual radioactivity due to their entering contaminated areas or their being exposed indirectly to this subtle hazard.

In no instance does this take into account the adverse psychologic effects to personnel which can certainly be estimated to be serious and which may indeed prove to be a major concern. This will depend very much on how well these effects can be minimized by adequate indoctrination smooth organization and leadership. It is impossible to make a good estimate of this phase of the anti-personnel effect.

FIELD INSTRUMENTS FOR THE DETECTION OF IONIZING RADIATION

GENERAL

Instruments

The detection and measurement of high energy ionizing radiation depends entirely upon suitable instruments and photographic film. Without these, even intense radiation will not be recognized until serious damage has been done. It is important, therefore, that the monitor have a thorough understanding of the principles of operation and limitations of available instruments.

The three radiations, alpha and beta particles and gamma rays, cannot be detected and measured with equal facility. Alpha particles, because of their short range, will not be measured with the usual portable instrument. Ionization chambers with windows of thin mica or stretched nylon 0.0001 inches thick will measure alpha particles, but a practical field instrument incorporating this feature has not been developed. The proportional counter will also measure alpha, but it can hardly be considered a field instrument because of its size. Beta particles and gamma rays can be determined with a single Geiger tube instrument; by opening a window in front of the tube both radiations will be measured, but only gamma will penetrate with the window closed. Most portable ionization chambers are designed to measure only gamma rays since constructional strength would be lost if thin walls were used which would permit beta particles to penetrate into the ion chamber. The same is true of electrometers and electroscopes.

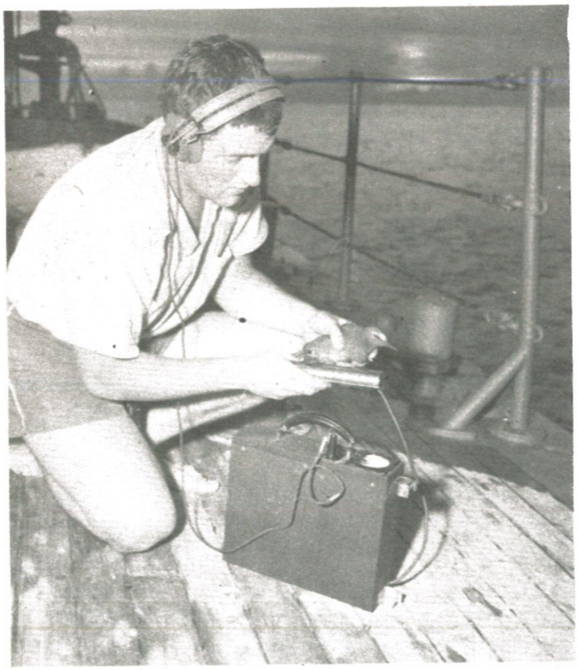
The essential requirements of a field instrument are portability, ruggedness and dependability. It must be simple in operation so that personnel can be rapidly trained in its use. It must be so designed that repairs and replacement of parts can be accomplished in the field. The instruments at present available for survey work fall into four groups.

Following are some of the general characteristics of existing instruments.

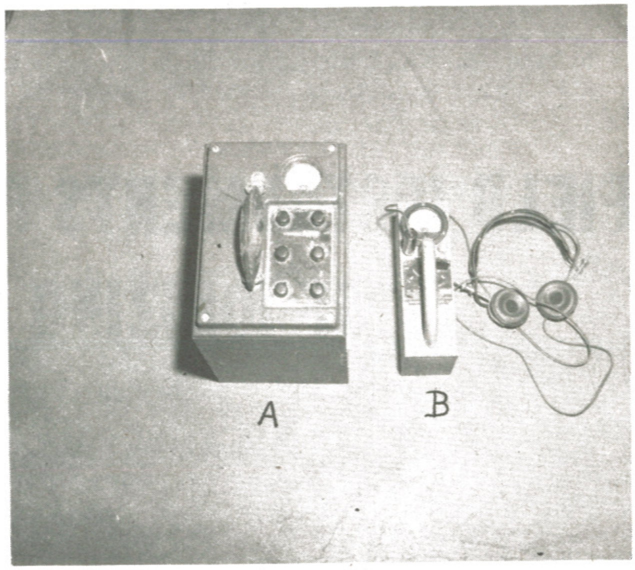
Geiger Counters

Geiger counters have been designed for field use as small as 250 cubic inches and with a weight of only 2 to 4 pounds.

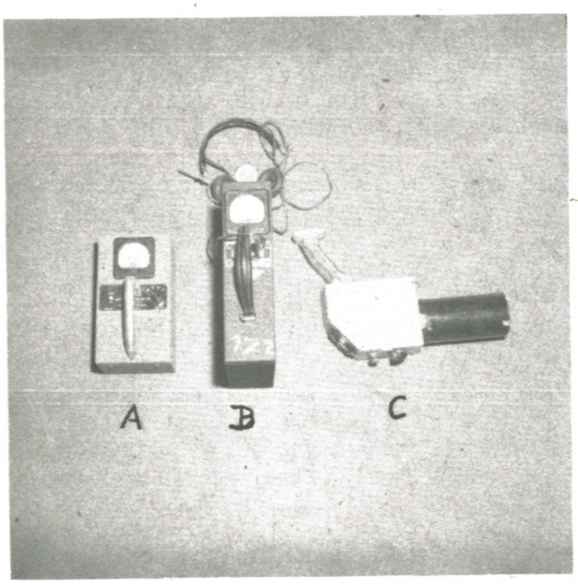
This instrument contains its own portable batteries. In most designs, ear phones are provided for audible detection in addition to a meter for scale readings. The scale has a range of from 0.001 to 0.5r per day, but by means of the ear phones it is possible to measure intensities about 1/3 or 1/5 as great. Thus this instrument is a rate meter



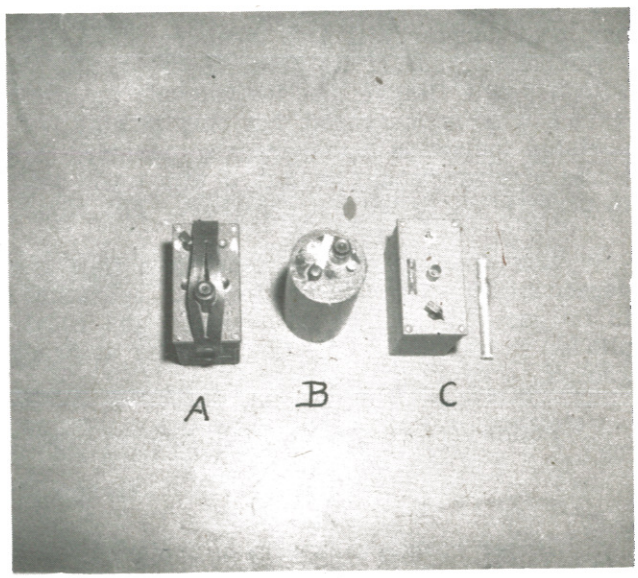
Geiger Counter in Use



A--Ion Chamber
B--Geiger Counter



A--Survey Meter
B--Geiger Counter
C--Beta and Gamma Meter



A--Dosimeter
B--Survey Meter
C--Charger and Pencil Electroscope

for measuring low levels of radiation. It is usually designed with a window so that when the window is closed, only gamma rays are detected, and when the window is open both beta particles and gamma rays can be measured.

Ionization Chambers

Ionization Chambers have been developed for field use with a volume of about 1 cubic foot and weighing 17 to 20 pounds.

Some of the present models have three scales covering a range for 0.1 to 200r per 24 hours so that this instrument is used when high intensities are being measured. The present chambers are designed to measure only gamma radiation.

Electrometers

As contrasted with Geiger tube and ionization chamber instruments which are ratemeters, the electrometer measures total radiation. It is commonly called a dose meter or dosimeter. Common types are small (100 cubic inches) and light (2 to 4 pounds), and they have an integral battery supply which charges plates in a detachable moisture-proof chamber. A sensitive voltmeter measures the charge on the plates which decreases through ionization by radiation entering the chamber. This instrument measures gamma radiation and is calibrated to read roentgens directly. It can be carried into the field and will indicate the total amount of radiation (dosage) to which a person is exposed in its vicinity.

Electroscopes and Film Badges

The field adaptation of the electroscope is a small pencil sized tube with no integral voltage supply. It is initially charged by a battery which orients a thin quartz fiber within the tube. As this charge diminishes through ionization by radiation, a thin fiber moves across a scale which can be viewed through a small end window in the tube. The scale divisions traversed by the fiber can be converted into roentgens. The instrument can easily be carried in a pocket and will supply continuous information concerning the accumulated radiation exposure (dosage) of its wearer. It is therefore, a dosimeter, and is sensitive only to gamma radiation, unless the chamber is made permeable to beta particles as well. It is usually made so that 0.1 rotentgen will produce about one half of full scale deflection.

A valuable supplement to the ratemeter and dosimeter is the film badge. Photographic film is sensitive to beta particles and gamma rays; in addition, by treatment of the emulsion with dye and addition of boron, it can be made sensitive to alpha particles and neutrons. The film, in the form of a badge, about 1" x 2", can be worn by personnel or placed in areas where radiation exists or may be expected. It also contains a lead cross to intensify the gamma radiation. It provides an accurate and permanent record of total exposure and therefore may be regarded as a dosimeter. It is easily handled and calibrated and requires no complicated electrical equipment.

These are only a few of the tools of the "Monitor" whose duty it is to detect and report the hazards, their location and intensity. The electroscope and the film badge are worn by personnel likely to be exposed to ionizing radiation and measure the total radiation to which the individual has been exposed during the period they have been worn. The electroscope may be read directly at any time whereas the film must be processed by methods similar to that used in developing X-ray films. The density of the film is proportional to the amount of exposure it has sustained and this is accurately measured by photoelectric methods using a so-called "dosimeter". The electroscope and film badge are normally worn simultaneously and act as a check on each other.

There are many other types of detectors but most of them are not field instruments. Since monitoring is not usually the duty of medical personnl, other types will not be described here. More detailed association with them and some practice in the use of the field type of instruments will be reserved for more advanced and personalized forms of instruction.

CALCULATION OF RISKS IN CONNECTION WITH RADIOLOGICAL HAZARDS

In the event of atomic warfare, commanding officers may be forced to accept certain calculated risks in a manner similar to that of other dangerous military operations.

In this respect the problem is essentially no different although certain techniques make the calculation more satisfactory than in operations not involving radiological safety.

This calculation can be employed only in connection with the entry into, or the occupation of contamination areas.

The basis for the calculation of the risk will be:

(a) Radiological survey of the area or the individual site. It may apply to collective safety as far as a unit of troops is concerned or the specific hazard to which a rescue party may be exposed in the conduct of its mission.

(b) The consultation of the RadSafe officer with the medical officer and the presentation to the commanding officer of the recommendations arrived at from the analysis of the radiological survey.

(c) A scale indicating probable injurious effects of various doses of exposure.

There are many factors to be considered:

Time After Detonation

Radioactivity will be most intense shortly after the detonation and will decrease markedly the first day, generally in accordance with regular curve, as previously noted. The residual effects from an air burst will be practically nil. In the case of the water burst, however, entry into or occupation of the areas of contamination would require a particularly careful calculation of the risk because of the greater inherent danger of high and persistent residual activity. Several months after a detonation of this type, the danger of internal radiation is likely to be more serious than the hazard of external radiation. The estimation of the alpha hazard is much more difficult (as previously noted) and requires very special techniques. A number of specialists and a great deal of time are required to make these estimates.

Reliability of RadSafe Organization

Unless survey data is reliable, proper calculations of risks cannot be made. This requires that good judgment be employed not only in assessing the intensity of the hazard but also in interpreting the reliability and the suitability of the data presented. This will necessitate the employment of personnel who are properly trained and technically and personally reliable. Instruments must be reliable and their use must be in accordance with standard procedure.

In the absence of any or all of the above, the problem of calculating the risk may be insurmountable. In this event, it is best to assume conditions of relative safety if it is an air burst of the Japanese type, and so serious as to contradict entry or occupation if a surface or water burst of the type seen in New Mexico or at Bikini. In the latter,

only the gravest and most vital mission could be entertained since the risk would be so great as to put the venture in the nature of a suicide project.

Dosage of Exposure and How Employed in Calculating Risk

The importance of the "time and concentration" factors, and the importance of "total amount of radiation received" in total body radiation has already been pointed out. It is worth while, also, to repeat that 0.1 R/day is the maximum total radiation which can be received with safety. The total dosage, then, is calculated by measuring the intensity of radiation at a given site or in a given area, and introducing the time relationship into the calculations in such a manner as to indicate the allowable time in that particular area.

For example, the intensity at site (a) according to the reading of a reliable meter is 100 R/day, in 24 hours, an individual would receive 100 r; in 12 hours, 50; in 1 hour, 4; in 15 minutes, 1 roentgen, etc. Thus an individual would receive ten times the maximum allowable dose of exposure in fifteen minutes in area (a).

Low Grade Hazard as in Normal Safety Operations.

In a controllable situation, the pocket dosimeter (electroscope) and the film badges are worn. If either or both of the devices should indicate that the individual wearing them had been exposed to 0.4 roentgens during any given working day, it would be necessary to remove him from any area containing radiation hazards for a minimum period of four days. In cases of marked over exposure, the following table may be used to estimate the result assuming that the over exposure has been accumulated over a relatively short period such as several weeks:

0.1 r/day - - - - - - - - - - - - - - -	Maximum safe exposure.
0.1 to 10 r/day - - - - - - - - - - -	relatively little risk.
10 to 25 r/day - - - - - - - - - - - --	some injury likely but probably not incapacitating.
25 to 100 r/day - - - - - - - - - --	injury practically certain, probably incapacitating.
100 to 300 r/day - - - - - - - - - - -	serious injury, some deaths practically certain but may be delayed.
300 to 600 r/day - - - - - - - - - - -	serious injury or deaths certain, very serious incapacitation, some may linger for weeks or months requiring extensive medical attention and even then die.
600 to 1,000 r/day - - - - - - - - - -	death certain, usually in first 24 hours.
above 1,000 r/day - - - - - - - - - --	death certain, usually in a few hours.

Internal Body Radiation

The maximum quantity of radium-like material which may be safely ingested as established by the Manhattan Engineer District scientists is one (1) microgram in an entire life time.

Interpolation of Meter Readings into Maximum Allowable Working Times

Personnel working in contaminated areas should not stay in these areas any longer than the time indicated in this table

Column No. 1	Column No. 2	Column No. 3		
R/d at	R/h For 24 hours day	Maximun allowable length of time for personnel working in Radio-active areas of intensity R/d shown in Column No. 1 for every 24- hour period.		
Working Point		Hours	Minutes	Seconds
100	4.166666	0	1	26
90	3.750000	0	1	36
80	3.333333	0	1	48
70	2.916666	0	2	3
60	2.500000	0	2	24
50	2.083333	0	2	53
40	1.666666	0	3	36
30	1.250000	0	4	48
20	0.833333	0	7	12
10	0.416666	0	14	24
9	0.375000	0	16	00
8	0.333333	0	18	00
7	0.291666	0	20	34
6	0.250000	0	24	00

Column No. 1	Column No. 2	Column No. 3		
R/d	R/h For 24 hours day	Maximun allowable length of time for personnel working in Radio-active areas of intensity R/d shown in Column No. 1 for every 24-hour period.		
Working Point		Hours	Minutes	Seconds
5	0.208333	0	28	48
4	0.166666	0	36	00
3	0.125000	0	48	00
2	0.083333	1	12	00
1	0.041666	2	24	00
0.9	0.037500	2	40	00
0.8	0.033333	3	00	00
0.7	0.029166	3	25	00
0.6	0.025000	4	00	00
0.5	0.020833	4	48	00
0.4	0.016666	6	00	00
0.3	0.012500	8	00	00
0.2	0.008333	12	00	00
0.1	0.004166	24	00	00

Column No. 1--Values from Calibration curves of instrument.

Column No. 2--Values of Column No. 1 divided by 24.

It will be noted in the pages which follow that there is a moderate amount of repetition. This is intentional. Certain of the medical aspects are of such importance and certain factors so easily neglected that the added emphasis of repetition is considered essential.

MEDICAL ASPECTS OF AN ATOMIC EXPLOSION

THERMAL BLAST

Thermal blast refers to the radiant energy of the atomic explosion and does not include the effects of secondary fires or explosions which may be the result of the detonation. At the instant of the detonation, unmeasured degrees of heat and light are produced. Both the infra red and ultra violet rays are capable of producing severe burns to the body surface, especially to exposed surfaces of the skin. The thermal energy is, however, of very short duration and, altho it may account for a high proportion of the casualties near the center of the detonation because of its extreme intensity, a relatively small amount of shielding offers considerable protection. Even light clothing, especially if glossy surfaced, offers complete protection in many cases. Dark colored materials, on the other hand, will frequently char or burn. Frequently, cases were found among the Japanese where the skin was burned in a regular pattern depending upon the color and consistency of the clothing which had been worn at the time of the blast. It has been estimated that between twenty and thirty percent of the fatalities at Nagasaki and Hiroshima were the result of flash burns.

AIR BLAST

The primary type of air blast injuries are produced by the passage of the pressure wave thru the tissues causing actual structural change and injury or death. These effects are exerted chiefly at interphases between air and solid as in the lungs, the intestines, or the stomach. Except for individuals in close proximity to the point of the burst, the primary effects are of little importance. At ranges where they might be considered dangerous, other factors would be of more importance as casualty producers. That is, an individual well beyond the limit of danger from primary air blast might still receive many times the lethal dose or radiation.

SOLID BLAST

The secondary air blast effect is far more important than the primary. Casualties are produced by (a) the structural collapse of buildings, (b) flying debris, (c) the effect of being hurled against solid or semi-solid substances. All of these injuries would be essentially the same as those produced by any heavy air blast.

In an underwater detonation, the energy transmitted thru the water would cause injury similarly to personnel in the water at the time and within the concussion range. An individual completely submerged is able to withstand many more pounds of pressure per square inch than one only partially submerged. In the latter, rupture of the hollow organs is much more likely to occur. The exact range at which this type of casualty may be produced is not accurately known but it is much less than would normally be imagined, according to preliminary reports of research on the subject. In this connection it is interesting to note that, in the Bikini test, the air containing bladder which is

part of the floating mechanism of fish, was, in many cases, ruptured and the fish were subsequently found on the bottom of the lagoon by divers.

RADIATION BLAST

Introduction

Recently there has been a great deal of interest in the biologic effects of the various forms of ionizing radiations and of neutrons. Individuals exposed to injurious dosages of these radiations present a variety of clinical conditions. Important in determining the clinical expression of the changes produced is the manner in which the injurious agent is brought to bear on the individual. Exposure of the external surface of the body to penetrating ionizing radiations and neutrons causes quite a different set of clinical findings from that caused by internal body radiation. While there is some general relationship among the causative factors in that they belong to a group of related and interesting physical incitents, the clinical picture as a whole is usually more characteristic of the form of exposure than of the intrinsic characteristics of the injurious agent. Some of the clinical findings may be similar but the clinical picture as a whole is usually quite different. The classification presented is an arbitrary one and is aimed primarily at providing a terminology suitable for clinical diagnostic purposes.

Radiation sickness is the term used to describe the illness produced by over-exposure to penetrating ionizing radiation and neutrons. Systemic reaction, in this instance, arises from exposure of the external surface of the body to penetrating radiation. Gamma rays, x-rays and neutrons are the more common causative factors. The injurious dosage may be received instantly or may be accumulated over a period of time. The onset of symptoms may be abrupt or insidious. In the acute form, as observed at Hiroshima, it may be fulminating. In the mild form observed after roentgen therapy, the symptoms are usually transient. One particularly subtle form sometimes seen is the leukemia which occurs in radiologists after years of repeated exposure to low dosage of x-rays.

Radiation injury is the term employed to describe localized injurious effects which are not ordinarily associated with any systemic reaction. The incitants may be alpha or beta particles, gamma rays and x-rays. The onset is usually insidious. Some forms of radiation injury may be associated with radiation sickness, e.g., epilation in victims at Hiroshima. Other examples are precancerous lesions of the skin from prolonged and repeated exposure of a particular area to radium or x-ray, sterility from exposure of the testes to x-ray, and changes in the nails and finger prints from prolonged exposure locally to radium or x-ray.

Radioactive poisoning is the term used to describe the illnesses which result from radioactive materials gaining access to the body. Here they act as an internal poison producing localized or systemic effects or both. The offending radioactive poisons are materials which emit nuclear particles (alpha or beta) or nuclear radiation (gamma). The former in spite of their short range are of particular importance in this connection because of their high intensity of ionization. The onset is usually insidious, often subtle, and at times indeed it may be years after the original exposure. In experimental animals relatively massive doses can produce an abrupt onset. Examples of radioactive poisoning are the radium dial painters illness and poisoning due to drinking radioactive waters. In mining pitch blend, lung tumors occur as a result of inhaling radioactive dusts. Such lesions may remain localized for a long time before systemic effects appear. Radioactive poisoning might occur from misuse of radioactive isotopes in attempted therapeutic procedures. If the radioactive fission products from a nuclear explosion were to gain access to the human body in sufficient amounts, it is likely that the individual would present much the same clinical picture as that presented by the radium dial painters.

Definition

Radiation sickness is observed in individuals who have been exposed to external body radiation in amounts sufficient to produce systemic reaction. The clinical findings are characteristic. It may be acute or chronic in its clinical course. It may be so mild as to cause only a few hours illness or so severe as to be fatal within a like period of time.

Incidence

Radiation sickness was first observed subsequent to the introduction of the x-ray. As such it occurred as an accidental affair, due in the main to limited knowledge as to the requirements of safety. As the x-ray and the external radiation of radium were seen more and more in the treatment of various clinical conditions, particularly deep seated neoplasms, the outstanding characteristics of radiation sickness became more clearly recognized. The high incidence of radiation sickness at Hiroshima and at Nagasaki provided an opportunity to study radiation sickness as it occurred in a large group of people who had been exposed enmasse (a) to total body radiation and (b) to varying dosages of such exposure. With the advent of atomic warfare, radiation sickness has taken on a new significance.

Radiation sickness may be encountered in clinical practice following deep roentgen therapy or after the use of radium. As a consequence of accidental over-exposure, it may be observed in personnel employed in industrial plants where an external radiation hazard may exist due to the use of x-ray or radium in the checking of metal castings. In experimental laboratories, or wherever they operate power x-ray machines, cyclotrons, or a uranium pile, radiation sickness may follow an accidental exposure to various forms of ionizing radiation.

Etiological Considerations

Because of the close association of radiation sickness with the explosion of an atomic bomb, there is a fairly widespread impression among non-medical individuals that radiation sickness is a new disease entity born with the atomic bomb. Such is indeed not the case. Radiation sickness has long been recognized as a clinical entity by the roentgenologists. The exact mechanism by which ionizing radiations and neutrons produce injury in living cells is not known. Nor do we have specific therapeutic measures which can be employed to counteract the injurious effects of irradiation within tissues. On the other hand there is nothing particularly mysterious as far as the clinical manifestations of radiation sickness are concerned. Many illnesses are not so easily recognized or so well understood.

Intensive studies conducted on the casualties at Hiroshima and at Nagasaki, while yielding little new information which may be regarded as basic in character, nevertheless, have provided valuable information which confirms, or adds to, our previous understanding of radiation sickness.

Gamma radiation, quite similar in nature to the x-ray, was the most significant form of radiation, although it is not unlikely that the neutron radiation was also of greater importance than may now appear. Some individuals were exposed to a combination of gamma rays and neutrons, and some to infra red and ultra violet energy as well. No one was exposed to neutrons alone. Although we do have considerable information on the effects of both fast and thermal neutrons on living tissue, we do not have as much information as we have on radiation by gamma ray and x-ray.

EXTRINSIC FACTORS INFLUENCING RADIATION EXPOSURE

Radiosensitivity

As far as the individual is concerned there are certain intrinsic factors which determine the degree, or pattern, of cellular response to a given form and dosage of radiation. Tissues particularly susceptible to radiation injury are described as being radiosensitive and those least sensitive as radio-resistant.

There is considerable variation in radiosensitivity among species, organs, and cells.

(a) Species. -- The guinea pig and the rat are much more sensitive and the goat about equally sensitive with man. Fish are much less sensitive to radiation than man. As a consequence, the results of animal experimentation are not always directly applicable to man.

(b) Organs.-- The lymph glands, the bone marrow, the testes and the ovaries are the most sensitive organs. The hair follicles are more sensitive than the surrounding layers of skin. The brain, characterized by an extremely highly organize cellular tissue, is peculiarly resistant to radiation, the muscles somewhat less resistant.

(c) Cells.-- For a given type of cell, the more immature it is the more radiosensitive it tends to be. The most sensitive cells in decreasing order of sensitivity are lymphocytes, germinal cells of testes and ovaries, granulocytes, platelets and erythrocytes. The formed elements within the circulating blood are slightly less sensitive than those within the hematopoietic tissues. Somewhat less sensitive than any of the preceding cells are certain epithelial cells and the endothelial cells. As a consequence cytologic blood studies provide the earliest and most reliable indices of the clinical state.

IONIZATION IN LIVING TISSUES

Penetrating Radiations

It is customary to refer to hard electromagnetic radiations and neutrons as penetrating radiation. Gamma rays, x-rays and neutrons by themselves exert no biologic effects. Such changes are produced entirely by virtue of the charged particles which these radiations produce as secondary products. These secondary products in turn directly, or indirectly, produce ionization within the tissues.. Nuclear radiations produce no effects on living tissue other than those produced by fast charged particles.

Neutrons produce heavy charged particles (alpha and beta particles, protons, other charged nuclei) as secondaries in living tissue. These produce highly destructive dense local ionization often referred to as "columnar ionization"

X-rays and gamma radiation both produce light charged particles (electrons) as secondaries in living tissue. These cause ionization which is far less dense. On the other hand they are biologically very active as they cover a much greater volume than that caused by the heavy charged particles.

ETIOLOGICAL CONSIDERATIONS IN CONNECTION WITH THE PATHOLOGICAL CHANGES PRODUCED BY IONIZING RADIATION.

Under the microscope, tissues which have been damaged by radiation appear the same qualitatively regardless of whether incurred in therapeutic irradiation with x-ray, from over-exposure to radium, from exposure to the ionizing radiations of an atomic bomb, or as a result of bombardment with the neutrons from a cyclotron. The tissue

response is the same qualitatively no matter which the form of radiation as long as it is penetrating external radiation.

In the intensity of the injury received, and quantitatively as far as depth and extent of injury is concerned, the changes may vary materially.

If the dosage of the exposure is great enough to have any biologic effect, this is produced through the formation of ion pairs as a consequence of their effect on the protoplasm of the cells involved. It is likely that the processes of normal cellular metabolism are interfered with through the disruption of enzyme systems essential to the normal living of tissue. Cells may be killed or simply injured by ionizing radiation.

General Consideration of Cellular Pathology

The cellular changes which are observed in tissues injured by radiation are not in themselves pathognomonic of radiation injury. As a matter of fact there may be close similarity between the cellular changes produced in tissue by radiation with those produced by other forms of trauma, such as thermal burns, chemical poisons, infections, and extremes of malnutrition. Quite naturally tissues vary in their response to insult by these various agents. No other single agent, however, produces the same type of injury in the same diversity of tissues in the same individual. The changes produced in like tissues of different individuals may be so alike as to be indistinguishable and yet the injurious agents quite different. In this respect the testes of the males at Hiroshima often provided interesting changes in the reproductive cells. However, similar changes were found in the testes of many prisoners of war of the American and Japanes as a result of malnutrition. Furthermore, the bone marrow of a patient dying from benzol poisoning, or from agranulocytosis, may be in itself quite indistinguishable pathologically from the bone marrow of a fatal case of radiation sickness. It would be unwise to make a pathological diagnosis of radiation injury based on the failure (or response) of a single organ. Caution must therefore be exercised in evaluating the etiologic implications involved in a consideration of the changes observed in similar tissues, or organs of different individuals.

For purposes of this manual, it is not considered necessary or advisable to go further into a discussion of the gross or microscopic pathology. Since the tissue changes are no different from those produced by penetrating x-rays, the reader is referred to the various publications on the pathological effects of x-rays and radium if more detailed information on the subject is desired. It might be of interest to note here that, prior to the atomic explosions in Japan, autopsies were not, as a rule, conducted there. Many of the victims of the bomb were subjected to a careful post mortem examination, however, and a quantity of material was made available for study after the surrender. Several very interesting papers are now in the process of preparation and will shortly be available.

Clinical Features and Clinico-Pathologic Findings.

It is relatively simple to visualize the clinical findings and clinical course which is characteristic of radiation sickness on the basis of the sensivity of the cells and organs involved and their reaction to this form of injury. The remarks which follow present the outstanding features as they were observed subsequent to the air burst in Japan. They are essentially what the expert Radiologist would have anticipated.

Severe Exposures: Earliest Deaths.

In the most severe cases, death may occur within a few hours. Severe weakness and prostration, a state of extreme shock and a dulled sensorium with little else in the way of clinical or pathological findings is characteristic of this group. There may be fever. The exact mechanism of injury and death in this type of case is not understood.

The clinical picture, however, is clear cut, the prognosis completely bad. This type of severe exposure had rarely been seen in the human prior to the Hiroshima incident. In an attempt to rationalize possible therapy, there has been much speculation as to the underlying abnormalities of the physiologic processes. Some investigators believe that the mechanism of injury is interference with cellular respiration or the wide scale disruption of the enzyme systems which are concerned with the metabolism of the nuclei of cells and, in particular, the metabolism of nucleic acid. Others suggest that in the earliest deaths, the same mechanism may be involved which some believe to account for the severe and early states of shock encountered after extensive skin burns and after severe exposure to liquid mustard gas or Lewisite. In the latter instance, it may be that the cholinesterase enzyme is disrupted. Still others feel that there may be specific injury to the sympathetic or autonomic nervous system as a result of physical injury (radiation) or toxic injury (protein break-down products). There is some evidence to suggest that severe exposures to mustard gas produces similar toxic effects. Still others believe that the mechanism of shock here, as in other instances, is due to the intoxication of vital cells of the body as a result of the circulation throughout the body of the breakdown products of protein from cells injured by irradiation. The role of injury to the adrenal is not clearly understood as correlation of the pathologic findings with clinical expression is not clear cut. Some investigators believe this to be very important in the the early deaths.

Severe Exposures: Death During the First Week.

Individuals severely exposed but not as severely so as those just described, are likely to present varying degrees of shock, even within a few hours of the incident. Anorexia, nausea and vomitting, fever, and weakness and prostration may be the outstanding findings on the first day. There may be no evidence of skin injury. Pain and suffering are likely to be absent unless there is concomitant illness or injury. The sensorium is dulled and the individual is more likely to be apathetic than agitated. Death may occur on the second or third day. Blood counts taken a few hours after exposure may reveal a decrease in total leukocyte count and this decrease will invariably be noted on the second day. Before death, the count may drop to 500 or below. There may be a bothersome diarrhea beginning on the second day, rarely before. This will become progressive if the individual survives beyond this time. The diarrhea will be watery early but will tend to become bloody. Late in the first week, secondary infection and a tendency to spontaneous bleeding will become serious complications. Severe angina is not uncommon at this time. Ulceration of the tonsils, the mucosa of the large intestine and, in women, the labia may occur.

In general, the earlier the appearance of systemic reaction, the more grave the prognosis. The same is true of an early depression of the leukocyte count. Complications are of utmost importance but difficult to evaluate.

Severe Exposures: Death After the First Week.

In individuals who survive the first week, the initial symptons are not likely to be so severe or as early in their appearance. White blood counts will reveal an early suppression of lymphocytes followed by a decrease in the granulocytes. The accompanying graphs indicate the approximate results of the differential count. The total WBC may fall to less than 500. After the third or fourth day, a tendency to bleed may be an outstanding feature, and may be an important factor in determining the outcome. Hemorrhage may occur into any organ or from any membrane. Bleeding from the mouth and gums, intestinal bleeding, and hematuria are to be expected. There may be petechial hemorrhages into or under the skin, into the retina, the myocardium, or the cerebral tissues. This hemorrhagic tendency is associated with (a) a reduced number of platelets, (b) possibly some humoral disturbance involving an anti-histamine like substance, and (c) increased capillary permeability. The reduction of platelets and increased capillary permeability can be observed objectively.

During the later part of the first week and thereafter, various forms of secondary bacterial invaders may complicate the picture. Due to the supression of the lymphocytes and granulocytes and to the destruction of lymphoid tissue, there is a marked or completely absent resistence to infection. This may result in invasion of the intestinal mucosa by the normal intestinal flora, bacteremia, boils and carbuncles, ulceration of the tonsillar areas and angina with marked necrosis of the laryngeal tissue. Such lesions may reveal no lymphocytic infiltration only macrophage type of cells. In cases of thermal burns or other skin injuries, the secondary infection seriously delays healing and promotes the formation of scar tissue. This may become luxuriant and unique in its characteristics. It resembles keloid and it is thought that this scar tissue may be in the future become malignant.

It may be of interest to note here that an occasional case with an apparently grave prognosis may evidence some response to bacterial invasion and produce an elevation of the WBC. This would normally be considered a favorable sign since it would indicate that complete paralysis of the hematopoietic function has not occured.

In a patient who survives the first week, there is very likely to be a profound anemia which will be the result of a combination of failure of the erythropoietic tissues and loss of blood. Both the RBC and the hemoglobin will be reduced. In the more severe cases, there appears to be a complete paralysis of all marrow function and the clinical course and blood picture are similar to those found in fatal benzol poisoning and other forms of "panmyelophthisis".

Ingestion Type of Radiation

The symptomotology, prognosis, and treatment of the condition which results from the aspiration or ingestion of radioactive material are identical to those observed in the cases which resulted in the radium dial painters. Since these have been extensively mentioned and described in the medical literature, it is not considered necessary to review them here.

RECOVERY AND CONVALESCENCE

The more severe the illness, the longer recovery is likely to require. In the casualty and death producing ranges of exposure, there is very little individual variation and husky persons are not more resistant to the radiation that the less robust. In cases of less intensive exposure, however, where secondary infection, hemorrhagic tendency, etc., are so common as to be considered an integral part of the clinical picture, constitutional endowment, age, and some secondary external factors may be of great importance in determining the outcome of an individual case. Resistance to infection, local or generalized, is a variable factor and depends in part on the individual's resistance and in part on the characteristics of the invading organism, response to specific therapy, etc.

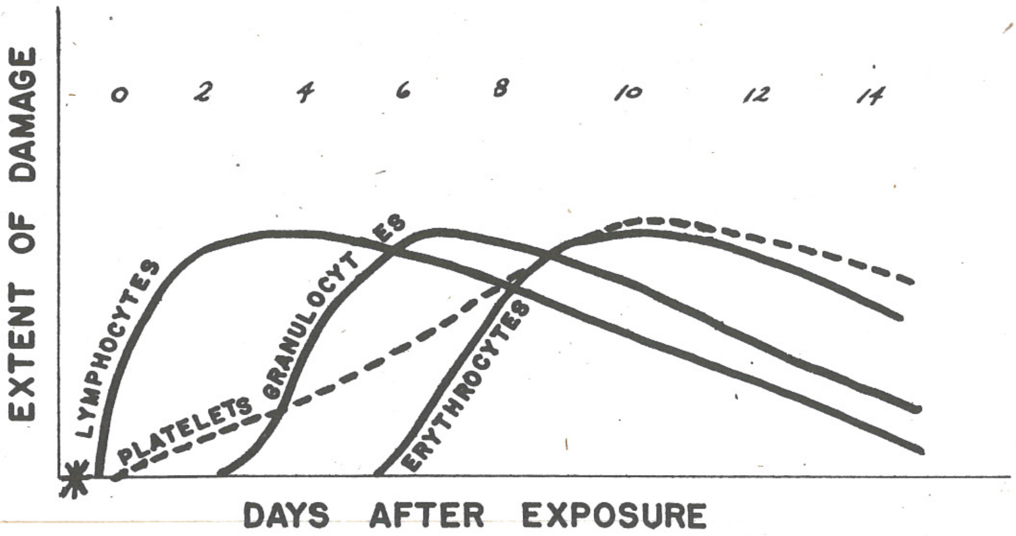
Changes in the intestinal tract may seriously hamper the assimilation of food and produce severe states of malnutrition. The intractibility of the diarrhea may assume very serious importance.

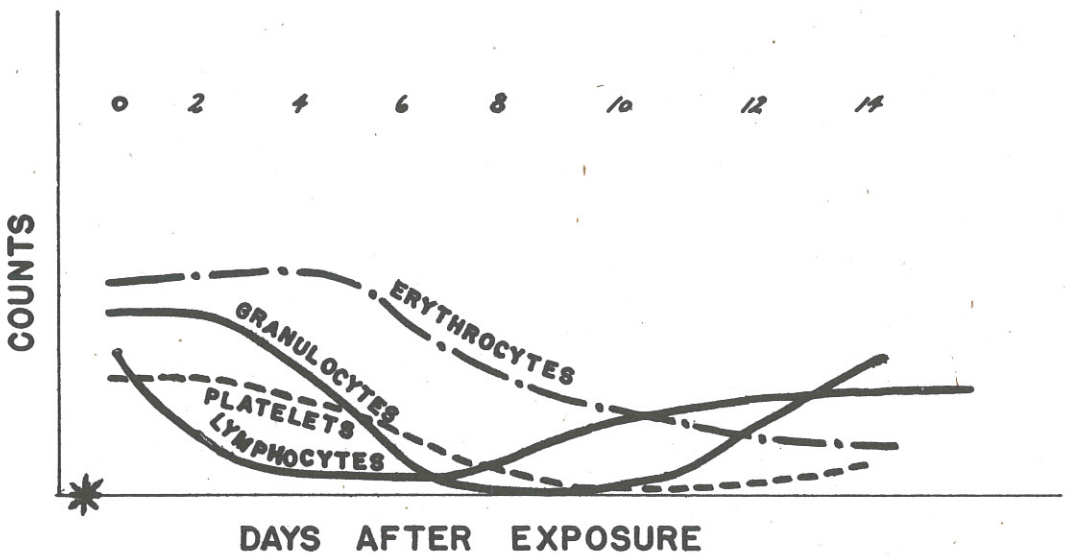
Generally speaking, no definite course of convalescence can be predicted. The more severe the combination of complicating factors, the more difficult and protracted the convalscence. Individuals who do not become ill during the first two weeks are not likely to become ill at all. Those who do become ill but are able to survive the sixth week are very likely to recover. The time element involved, however, and the therapeutic difficulties which might be encountered, are impossible of prediction.

The general behavior of the cellular elements of the blood stream is shown in the accompanying charts:

ACUTE RADIATION SICKNESS

SEVERE EXPOSURE — NOT FATAL





CHANGES IN FORMED ELEMENTS IN CIRCULATING BLOOD ARE CLOSELY RELATED TO LENGTH OF LIFE OF ADULT CELLS IN BLOOD STREAM.

Radiation Injury of The Hair Follicles and Skin.

An individual who has received enough radiation to produce erythema is quite certain to die of acute radiation sickness. The hair follicles, however, are much more sensitive to radiation than the skin and it is possible, in the case of smaller, non lethal doses, to produce epilation. Hair will be lost over the area exposed to radiation and, as has been previously noted under "geometry of radiation", the loss of hair may be unilateral. Epilation may occur prior to death in cases of fatal exposure when death occurs late in the illness.

Deaths in Relation to Time After Exposure

In Japan, the peak of the death curve occurred during the third week and fell gradually until the sixth week. Those who survived the sixth week had a relatively good chance of recovery and most of the deaths subsequent to that time were caused by secondary infections and were attributable to the impossibility of asepsis and antisepsis under the conditions which existed.

Overcompensation of The Blood Cells During Convalescence.

Occasionally, patients who have survived the first week of illness will be found to present an elevated leukocyte count as well as an increase in the hemoglobin and the total red cell count. The WBC may be 15,000 to 25,000, the RBC, 6 - 6.5 million, and the Hb, 110 - 125 % (Sahli). The elevated WBC is not necessarily evidence of infection. In these cases, the Differential count is thought to be of utmost importance, a count of less than 0.5% reticulocytes indicating a poor prognosis and one of over 1.0%, a good prognosis.

Overcompensation Not To Be confused with Chronic Exposures of Low Intensity.

That irradiation may cause either an increase or a decrease in the total count may be confusing. Severe acute exposures will cause a decrease followed, as recovery occurs, by an increase over the normal count. Low grade, chronic exposures produce an increase in the count unless the total accumulated dose is of such magnitude as to depress the function of the bone marrow. A few cases of this type were found among individuals living within an area where there had been an accumulation of "fall out" of radioactive materials. This same type of repeated exposure to x-ray is thought to account for the fact that leukemia is ten times more common in radiologists than in individuals not so exposed to radiation.

TREATMENT

Early treatment of survivors is likely to be impossible because of the difficulty of getting to the bomb victims, the probable lack of functioning medical facility, and to the lack of availability of trained personnel and of proper instruments and material.

Measures to be applied in the field before the casualty is removed to a medical facility. (aid station, emergency hospital, etc.)

(a) Do not needlessly expose rescue or aid party personnel to grave external radiation hazards. Do not attempt to remove patients to a "clean" area for treatment until decontamination has been accomplished to a safe degree.

(b) Protect against shock and administer simple life saving measures to acute cases where such is indicated and the situation permits.

(c) Transport to proper aid station or hospital as soon as possible. Do not attempt transfusions or intravenous procedures forward of the aid station.. Remember the dangers of infection.

Measures To be Applied in the Aid Station.

(a) Continue to protect against shock.

(b) Administer such life saving measures as may be indicated by good medical judgment and permitted by the situation.

(c) Select for whole blood transfusion only those cases in which medical judgment would indicate that some benefit could be derived. In cases which have patently received massive over-dosage, transfusion and heroic treatment is NOT indicated. Decisions will be difficult to make but, in case of an atomic disaster, it is most probable that trained personnel and all material (including whole blood) will have to be rigidly conserved and expended only on those who have some reasonable expectancy of recovering.

(d) If possible on the second day, select cases for further intensive care on the basis of white cell counts providing other hopeless findings are not over-riding. If a patient has a total count of less than 2,000, he should not be further transfused. If over 2,000, he should be selected not only for transfusion but for the best medical and nursing care that it is possible to provide. If, on the third day, the count has increased to 5,000, the chances of recovery are good but if there has been a further decrease, the chances are nil and no further expenditure of supplies is warranted. Total WBC is, then, a guide for prognosis and indicates those individuals who should be selected for "all out" treatment and those for whom treatment would be wasted.

General Considerations Applicable Particularly After The Second Day.

(a) Good nursing care, asepsis and antisepsis.

(i) Hygiene of the mouth and skin.

(ii) Avoidance of parenteral treatments if possible.

(b) Penicillin and sulfonamide medication, orally if possible.

(c) Streptomycin in cases of B. Coli invasion or bacteremia.

(d) Whole blood transfusions as indicated by blood studies.

(e) Folic Acid and Liver Extract to support the transfusions.

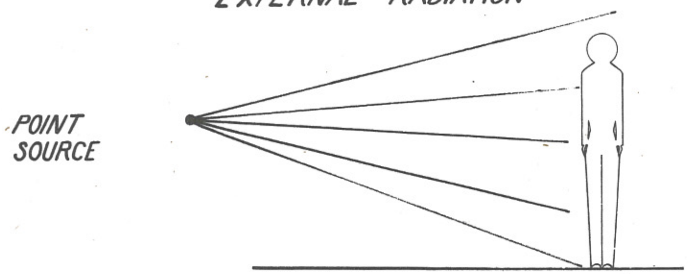
(f) Possibly, the administration of blood coagulents, Vitamin K preparations, Congo Red, etc. The use of these preparations in man had not been investigated but they may be found to be of some value.

The following is the final paragraph of the "Report On The Medical Studies Of The Effects Of The Atomic Bomb" by Dr. Masao Tsuzuki, Professor of the Tokyo Imperial University and Chairman of the Medical Section of the Japanese National Research Council:

"The most important measure for the treatment of the atomic bomb radiation injuries is careful protection. All patients are effected more or less by the radioactivity, these must recover by their own vital power. In the cases in which the vital organs are damaged beyond their ability to recover, medical care at the present time cannot help. We may have some hope of recovery as long as any reserve power is remaining because the radiation exposure has occurred only once. We must, therefore, avoid such treatment as whipping a tired horse hastily. In other words, we should not be over-confident in the ability of our medical care. Our aim shall always be a promotion of the natural healing powers."

1

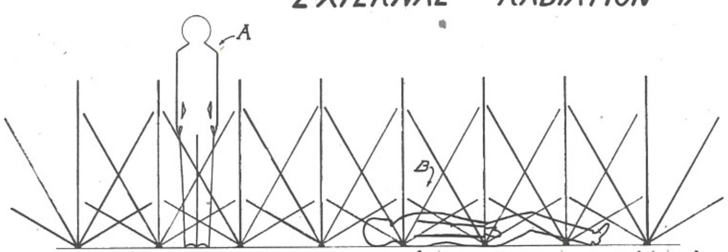
EXTERNAL RADIATION



DIRECT RADIATION
(POINT SOURCE - $\beta, \gamma, n.$)

2.

EXTERNAL RADIATION



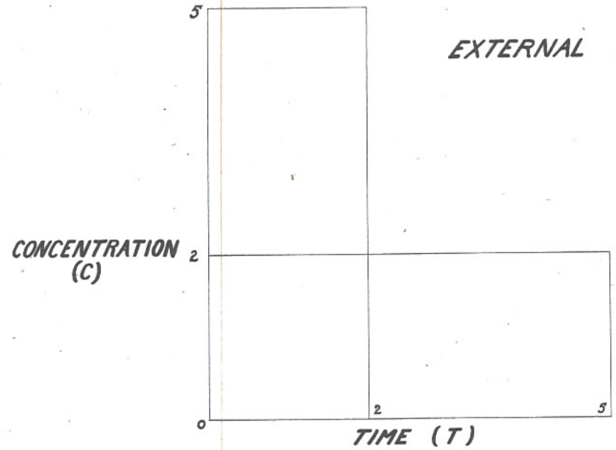
TOTAL BODY RADIATION (EXTENDED SOURCE) (β, γ)

A WHEN ENERGY IS WEAK, OR WHEN ONLY β RADIATION, THIS IS MORE IMPORTANT THAN THE CASE OF HIGH ENERGY γ RADIATION FROM THE SURFACE.

B LYING ON THE DECK MAY TURN A SLIGHT HAZARD INTO A SERIOUS ONE UNDER CONDITIONS OF A ABOVE.

3.

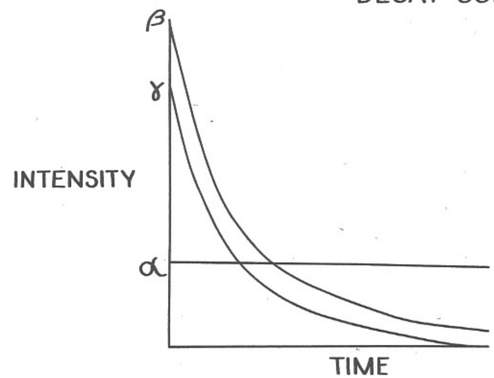
EXTERNAL RADIATION



CHEMICAL SYMBOL FOR TOXIC DOSAGE (CT) COMPARABLE TO TOTAL EXTERNAL RADIATION DOSAGE.

4

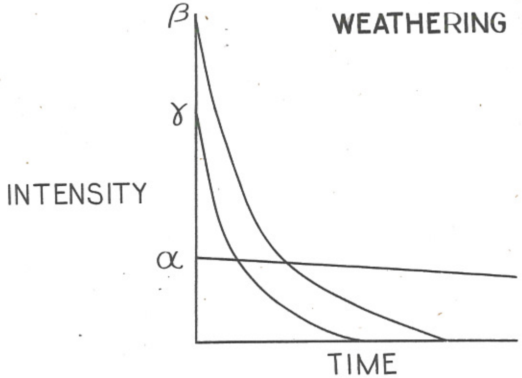
DECAY CURVE



INFLUENCE OF NATURAL RADIOACTIVE DECAY OF FISSION PRODUCTS AND FISSIONABLE MATERIAL, CONCERNING CHANGE IN HAZARD.

5

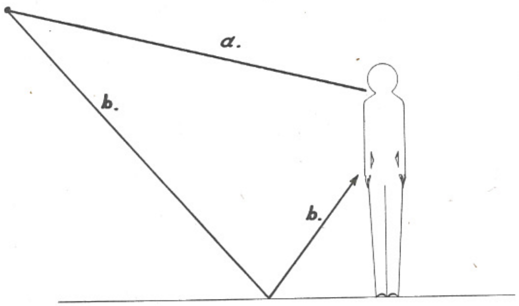
DECAY CURVE
WEATHERING EFFECTS



INFLUENCE OF WEATHERING ON THE CHANGE IN HAZARD. WEATHERING TENDS TO REDUCE THE HAZARD BY REMOVAL OF THE MATERIAL FROM THE CONTAMINATED SITE TO ANOTHER SITE.

6

EXTERNAL RADIATION



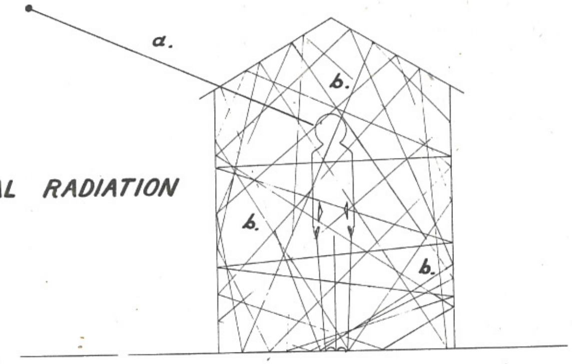
MAN IN THE OPEN

a. DIRECT RADIATION. (β, γ, n).
b. SCATTERED RADIATION. (β, γ, n).

IN THE MAN ONE SIDE ONLY IS EXPOSED WHEN THE RADIATION REPRESENTS AN ENERGY OF BELOW 2 MEV. IF THE RADIATION REPRESENTS AN ENERGY ABOVE 2 MEV, THERE IS PRACTICALLY AS MUCH RADIATION TO ONE PART OF THE BODY AS TO ANOTHER.

7.

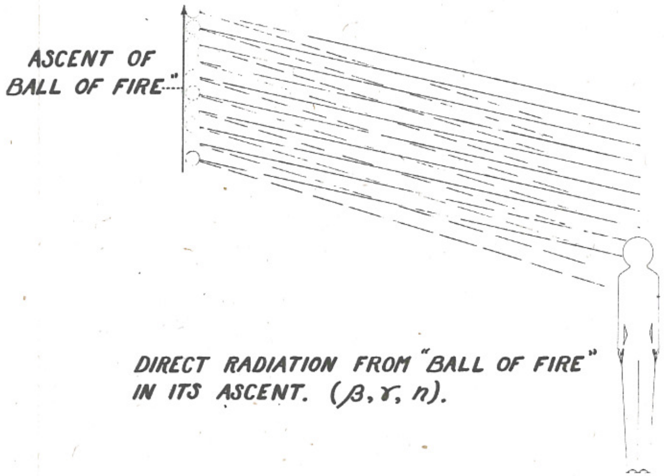
EXTERNAL RADIATION



MAN IN BUILDING (TOTAL BODY RADIATION)
a. DIRECT RADIATION (β, γ, n).
b. SCATTERED RADIATION (β, γ, n).

8.

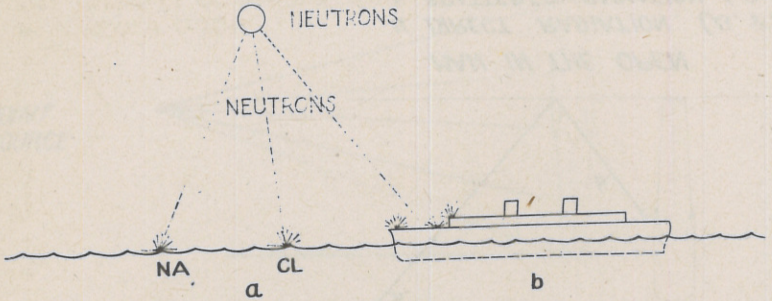
EXTERNAL RADIATION



DIRECT RADIATION FROM "BALL OF FIRE" IN ITS ASCENT. (β, γ, n).

9

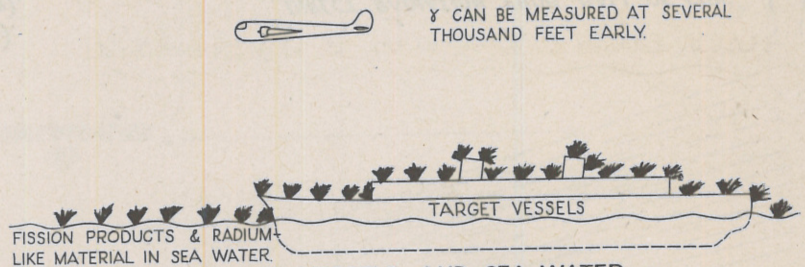
EXTERNAL RADIATION
(FROM RESIDUAL RADIOACTIVITY)



a. INDUCED RADIOACTIVITY IN SEA WATER (β, γ).
b. INDUCED RADIOACTIVITY IN SHIPS (β, γ).

11

COMBINATION EXTERNAL & INTERNAL RADIATION HAZARD
(FROM RESIDUAL RADIOACTIVITY)
(FISSION PRODUCTS)



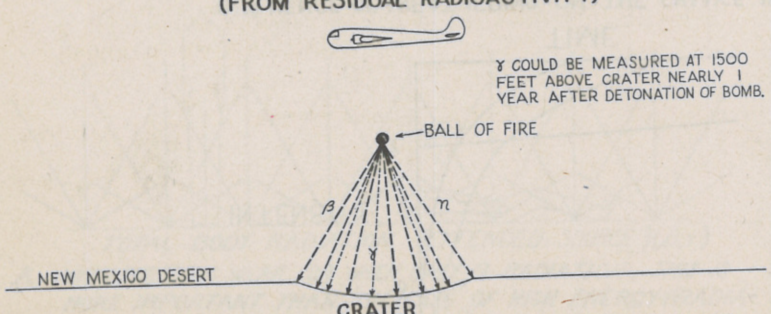
TARGET VESSELS AND SEA WATER

RESIDUAL RADIOACTIVITY RESULTING FROM THE DEPOSITION OF FISSION PRODUCTS IN AN UNDERWATER EXPLOSION.

EARLY THERE ARE STRONG γ RAYS IN ALL DIRECTIONS AND OVER EXTENDED RANGE. LATER THEY DIE OUT HAVING ONLY β RAYS AND α EMITTERS. EXTERNAL RADIATION HAZARD RECEDES, LEAVING INTERNAL RADIATION HAZARD NEARLY AS GREAT AS IT WAS IN THE FIRST FEW WEEKS.

10

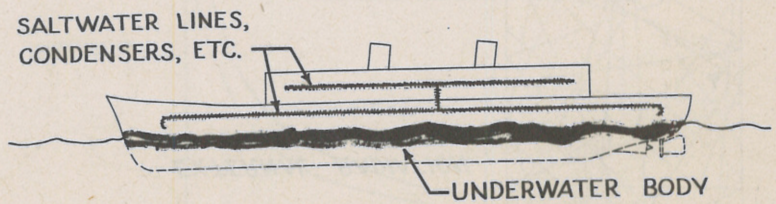
EXTERNAL RADIATION
(FROM RESIDUAL RADIOACTIVITY)



RESIDUAL RADIOACTIVITY RESULTING FROM A COMBINATION OF INDUCED RADIOACTIVITY AND DEPOSITION OF FISSION PRODUCTS, (NEW MEXICO TESTS, 100 FEET ABOVE GROUND).
a. INDUCED FOR A VERY SHORT TIME. (β, γ).
b. FROM DEPOSITION OF FISSION PRODUCTS A VERY LONG TIME (β, γ).

12

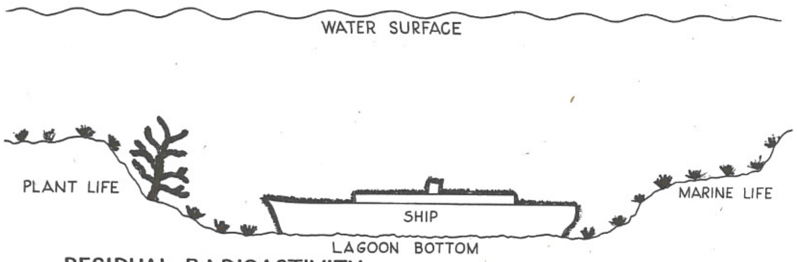
COMBINATION EXTERNAL AND INTERNAL RADIATION HAZARD
(FROM RESIDUAL RADIOACTIVITY)
FISSION PRODUCTS



NON-TARGET SHIPS

13

COMBINATION EXTERNAL & INTERNAL RADIATION HAZARD FROM RESIDUAL RADIOACTIVITY FISSION PRODUCTS

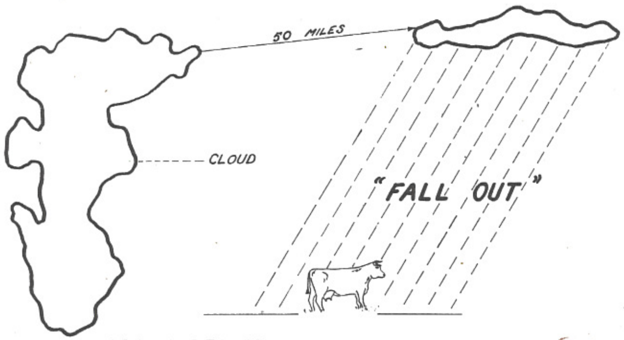


RESIDUAL RADIOACTIVITY

a. EARLY FISSION PRODUCTS ARE PRETTY WELL SCATTERED THROUGHOUT THE WATER AND ON THE SURFACES OF THE SHIPS. (β, γ, α).

b. AS TIME GOES ON FISSION PRODUCTS ARE CONCENTRATED IN MARINE LIFE AND IN ORGANIC MATERIAL IN THE BOTTOM (LESS γ, SOMEWHAT LESS β, RELATIVELY MORE α AS TIME GOES ON).

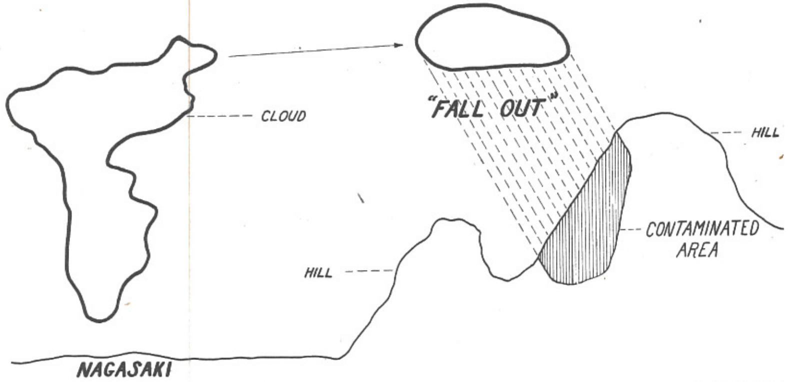
14.



NEW MEXICO DESERT

FINE PARTICLES OF MATERIAL CONTAMINATED WITH FISSION PRODUCTS FELL OUT OF CLOUD ARISING FROM TOP OF EXPLOSION COLUMN AFTER IT HAD TRAVELED 50 MILES TO THE NORTH EAST. IT WAS NOT A SERIOUS HAZARD ON THIS OCCASION.

15.

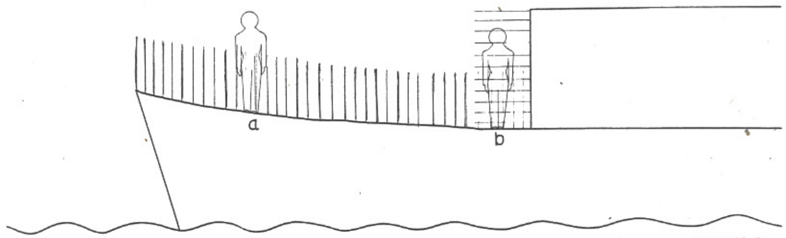


NAGASAKI

FINE PARTICLES OF MATERIAL CONTAMINATED WITH FISSION PRODUCTS FELL OUT OF CLOUD ARISING FROM THE EXPLOSION COLUMN AFTER IT HAD TRAVELED A FEW MILES TO THE EAST OF NAGASAKI. IT WAS NOT A SERIOUS HAZARD ON THIS OCCASION.

16

GEOMETRY OF EXTERNAL RADIATION

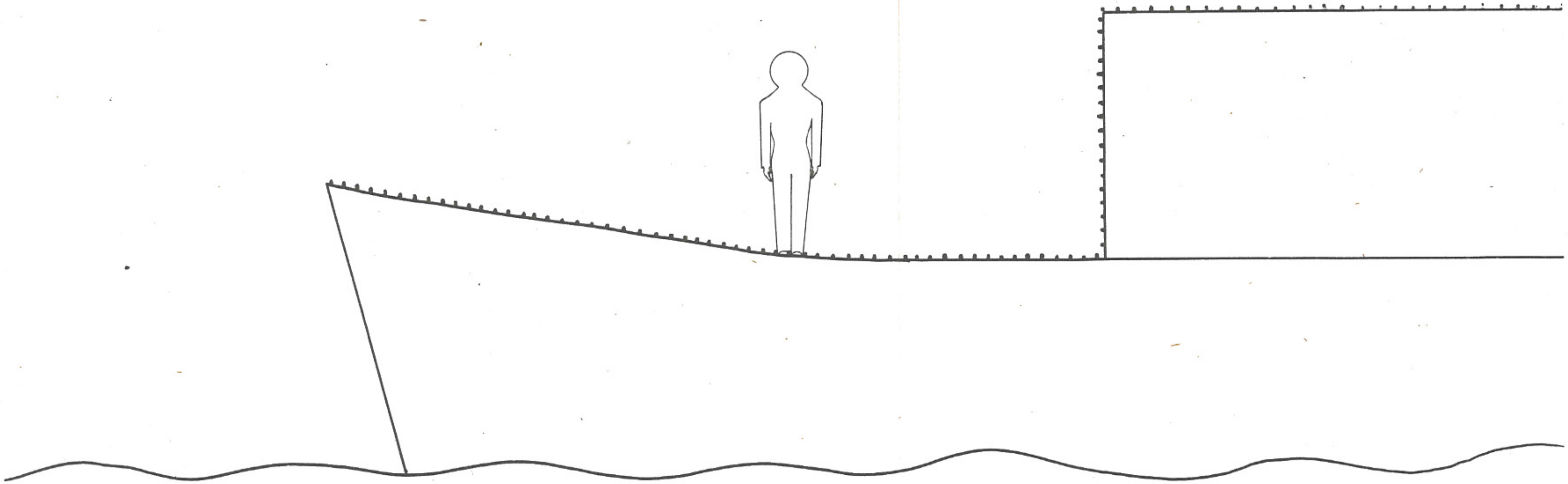


FISSION PRODUCTS ON THE SURFACE OF TARGET VESSELS

a. THIS MAN RECEIVES RADIATION (β,γ) ONLY FROM THE SURFACE OF THE DECK.

b. THIS MAN RECEIVES RADIATION (β,γ) FROM BOTH THE DECK AND THE BULKHEAD. STANDING NEAR SUCH A BULKHEAD IS AS BAD OR WORSE THAN LYING ON SUCH A DECK.

CONTRAST OF INTERNAL RADIATION AFTER EXTERNAL HAZARD IS GONE



FISSION PRODUCTS AND FISSIONABLE MATERIAL ON SURFACE OF TARGET VESSELS.

a. EXPOSED ONLY TO THE INTERNAL RADIATION HAZARD.

U. S. GOVERNMENT PRINTING OFFICE O—1947

It will be noted by the reader that this publication is very elementary. No attempt has been made to include in any detail any of the pathological, radio-chemical, or radio-biological implications of atomic energy. Radiological Safety is a highly technical specialty and it is not considered possible or necessary to train all medical officers as specialists. The Navy will require many such specialists, however, not only in the event of atomic warfare but also to insure protection of personnel in the production of atomic power for use by the Navy either ashore or afloat. The availability of advanced courses in Radiological Safety and related subjects will be announced from time to time in the BuMed NEWS LETTER.